Laboratory Simulation of the Deep-Ocean Environment

KENNETH O. GRAY*
U. S. Naval Civil Engineering Laboratory, Port Hueneme, Calif.

The laboratory simulation of certain aspects of the ocean environment is a necessity for research, development, and the testing of components, assemblies, and systems designed for undersea applications. However, even the most sophisticated ocean environment "simulation" facilities in existence do little more than simulate some of the physical parameters of hydrospace, such as hydrostatic pressure and temperature. Few, if any, of these facilities operate with fresh seawater as the fluid medium. Among the environmental factors not normally simulated are 1) the biota, 2) the seawater chemical system, 3) the infinite-volume effect of the ocean as an energy sink, and 4) the pressure vs depth gradient. The present state-of-the-art precludes little more than an appreciation of the biota problem, and permits only limited solutions to some of the others. These problems attendant to the laboratory simulation of ocean environments in pressure vessels will be discussed and some of the techniques used to solve them, at least partially, will be presented.

Introduction

LABORATORY simulation of the deep-ocean environment is required for testing of anti-submarine warfare (ASW) components, subsystems, and equipment in order that a high degree of reliability may be assured. Although this type of testing is costly and involves the use of expensive, highly specialized, and relatively complex facilities, it is still far cheaper than similar testing at sea. Unfortunately, no amount of testing in a tank of fresh water will provide any assurance that an instrument package will function properly when subjected to high-pressure, low-temperature seawater.

Facilities for deep-ocean environment simulation, or hydrospace simulation, as we shall call it, may be generally classified into three types: 1) hydrostatic-pressure test facilities, 2) partially-simulated hydrospace test facilities, and 3) facilities for the study of hydrospace via laboratory simulation of hydrospace. It is estimated that about 98% of the existing facilities fall in the first category. Most of them use hydraulic oil, fresh water mixed with soluble oil, or fresh water as the hydraulic fluid. Only a few attempt to test at realistic deep-ocean temperatures. Very few facilities fall in the second category, which requires that they operate with seawater and realistic deep-ocean temperatures.

The third type of facility, which requires the maintenance of realistic seawater chemical conditions, exists only on the drawing board. The problems involved in this type of operation are only now being explored, and their solution will require considerable research and probably some extension of the state-of-the-art.

Types of Tests Conducted in Simulated Hydrospace

Materials for use in hydrospace may be tested to determine the effect of the chemical environment (corrosion) on them at great depths and the effects of such an environment on their physical properties. The problems involved in establishing a suitable environment for valid corrosion studies are considerable and will require a concerted research and development (R&D) effort for their solution. A deep-ocean analog of the standard materials testing techniques is not in existence at the present time though no serious problems in this area are anticipated.

Structural and structural-component testing in simulated hydrospace may be static, cyclic, or dynamic. These are the types of tests most often conducted, and consist of subjecting structure or models to hydrostatic pressure under various loading conditions.

Bio-organism testing is being conducted under very limited conditions at present. The problem of providing an appropriate environment in a hydrospace simulator is the primary obstacle to this type of testing. A secondary, though difficult, set of problems is that of collecting deep-ocean organisms, maintaining them in good condition during transfer to a hydrospace simulator, and then observing their behavior while in the simulator. This is a field of endeavor and research which has as yet received very little attention except by a few scientists in some of the oceanographic institutions. Dr. Zobel at Scripps Institution of Oceanography has done pioneering work in this area with microorganisms.

Limitations on Hydrospace Simulation

What are the limiting factors that prevent us from simulating the deep hydrospace environment? Almost all of the limitations listed below stem from the fact that in the ocean there is, for all practical purposes, an infinite volume of seawater surrounding any object submerged at great depth, whereas, conversely, our laboratory pressure vessels contain a relatively small volume of fluid surrounding a disproportionately large object.

First is the problem of space. There are definite limitations both on how big a pressure vessel it is possible to build and how big a vessel one can afford to buy. This then is a strict limitation on any test program involving large structures. As a result of this, it is frequently necessary to resort to models.

Testing with models also presents some problems. In general there are two types of models; realistic and elastic. The realistic model is one whose performance is a scaled version of the full-size structure. It is constructed from the same materials using the same fabrication and joining techniques. It must be remembered however, that although the size of the materials can be readily scaled, the physical properties do not automatically follow suit. For example, the properties of steels in thin section are not the same as thicker sections of the same material. This is due to the metallurgical changes brought about in the reduction of section by rolling and other mechanical treatment. This is also the case in welds when the effects of welding thin materials are different from those of welding thicker sections of the same material.

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* Project Scientist, Deep Ocean Engineering Division, Civil Engineering Department.

The elastic model is one designed to look at one specific performance parameter, such as how the strains are distributed in a structure. These models are not necessarily fabricated from the same material as in the full-size structure. An example would be a plexiglas model of a submarine hull section built to examine the strain distribution around a hatch opening by use of photo-elastic techniques.

One technique sometimes used for avoiding the size limitations imposed by available pressure vessels is to test a large model or structure (intended for external pressure service) by generating a vacuum inside the object. Although the atmospheric pressure does place a pressure-differential limitation, the size is infinite insofar as "pressure-vessel" space is concerned. This method is appropriate for examining strain distribution in the low-pressure range and is commonly used to detect low-pressure leaks in large vessels. In the case of large structures, one has no other choice than to test in the actual deep-ocean environment.

Another problem unique to testing with models is that of scaling the pressure vs depth gradient. Suppose one is conducting a test with a realistic model of a vertically oriented, cylindrical object whose length is 50 times its diameter; in other words, a spar type of structure. In the real structure the surrounding pressure at the lower end may well be many psi greater than that at the upper end as consequence of the hydrostatic head. How does one scale this factor?

Second is the limited hydrostatic energy storage factor. The amount of potential energy available in a pressure vessel to collapse a test object is the sum of that which is stored in a finite volume of compressed fluid and the energy stored in the vessel walls due to their elasticity. Although considerable energy can be stored in a compressed fluid, it is infinitesimal compared to the potential energy available at a corresponding depth in the ocean. Those who have observed collapsing structures in pressure vessels know that one of the first indications of collapse, except in the case of brittle materials, is a decrease in the pressure in the vessel. Whether or not the collapse progresses is largely dependent on there being sufficient energy remaining in the fluid surrounding the object. An extreme example would be a 10-ft^3 object being tested in a 10.5-ft^3 capacity vessel. Unless the object was made of a brittle material like glass, the first buckling or plastic deformation would relieve the pressure in the vessel sufficiently so that the object would only partially collapse. This, of course, might be a real advantage if one were interested in preserving the object for purposes of studying the initiation of the failure. Obviously the hydrostatic pressure acting on a deeply submerged object in the ocean does not, for practical purposes, change as the object collapses, unless, of course, the object moves to a greater or lesser depth.

Third is the limited heat-sink capability. The problem of disposing of large quantities of heat generated by a test object, while at the same time maintaining realistic deep-ocean temperature conditions around it, may become serious when the amount of heat involved is great or the volume of the vessel is small. The rate of heat transfer through the fluid between the test object and the vessel wall and then through the vessel wall poses limiting conditions on such experiments. Although internal cooling coils in the pressure vessel are possible, they consume a considerable amount of high-cost vessel space. Again, this situation does not prevail in the real ocean environment.

Fourth is limited sound absorption. Suffice it to say that the testing and calibration of acoustical instruments can be complicated by reflections and reverberations caused by a small-volume, hard-walled pressure vessel.

Fifth is limited shock-wave absorption. Results from the study of shock-wave phenomena in a pressure vessel would be exceedingly difficult to extrapolate to the ocean environment. The reason is that, as in the case of sound studies, the reflection of the shock waves by the vessel walls, the elastic response of the walls, and the changes in water density and viscosity which would result from pressure changes would all combine to give anomalous results.

Sixth is limited chemical-energy storage. Seawater is a great deal more than fresh water in which an appropriate amount of various salts has been dissolved. Seawater contains live organisms, a suite of dissolved gases, various dissolved organic chemicals, and suspended organic and inorganic matter. As soon as a batch of seawater is removed from the ocean it starts to change both chemically and biologically. The native organisms die and decay, new organisms set up housekeeping, the dissolved gas system changes radically, the pH changes, and new chemical contaminants appear as a result of the new environment. Obviously, if the chemical composition of seawater is involved, as in a corrosion experiment, a continuous supply of fresh seawater with appropriate chemical properties must be supplied to the pressure vessel. A closed-loop vessel system cannot maintain a realistic seawater chemical environment. The chemical energy store upon which to draw just isn't there.

Factors Involved in Hydrospace Simulation

What then are the factors involved in the simulation of hydrospace and how well can we satisfy them? The principle factors are: hydrostatic pressure; temperature; seawater chemistry system—dissolved salts (salinity), dissolved gas content, dissolved organic materials, trace elements, pH, heat sink, and hydrostatic energy storage.

With the present state-of-the-art it is possible to simulate adequately the pressure and temperature only. The seawater chemistry system can be only roughly approximated by using fresh seawater and making some very limited adjustments in its properties. The heat-sink problem can be handled adequately by conventional refrigeration techniques only if the demands are small. Hydrostatic energy storage is another facet that can be handled to only a limited degree; this is accomplished by using a bank of accumulators connected to the pressure vessel.

Equipment

Pressure vessels are a basic requirement for the deep-hydrospace simulation. The choice of vessel operating pressure and size is governed by the user's requirements. Assuming that one desires to have a capability to test equipment for any ocean depth, the minimum pressure capability is in the order of 16,000 psi. If an overpressure capability is required, so as to determine experimentally if an adequate safety factor exists in objects to be tested, then an operating pressure of at least 20,000 psi is in order. However, a vessel with an operating pressure of 20,000 psi cannot be very large, something on the order of 10 ft in diameter being the upper limit without entering into an expensive R&D program to extend the state-of-the-art. A diameter of about 20 ft would, for the same reasons, be about the upper limit for a 10,000-psi vessel. With vessels of these sizes, it is doubtful if one could find more than one or two fabricators who could undertake their construction. A secondary problem, aside from cost, would be the very real one of transporting such a vessel to the user's facility.

For purposes of estimating the cost of large pressure vessels, a figure of $2.00/lb of vessel weight is useful. Weight, and therefore cost, increases generally as the square of the diameter. For a good grade of steel, such as HY-80, weight increases proportionately to pressure in the range 0–15,000 psi.

There are many techniques of fabrication available to construct pressure vessels. The most commonly used is the solid-wall vessel, machined from a forging. The layered type of construction is used most often in large-diameter vessels. Other types such as composite, filament wound, etc., are attempts to extend the size of pressure vessels beyond the limits feasible for solid or layered construction. For very large, high-pressure vessels, say in excess of 20 ft in diameter, the size and the weight alone require a fabrication technique that must be performed at the user's site. The transportation problem itself becomes virtually insurmountable for such large, heavy objects.

End closures and their restraints are also available in a variety of forms. Of those available, the bolt and tie-rod types are more suitable for small-diameter vessels in the pressure range 0–5000 psi. In the pressure range of 5000 to 20,000 psi, the threaded type is more desirable. For large-diameter vessels in the 0- to 5000-psi range, the most desirable are the clamp-band, shear-pin, and the shear-ring types. For large-diameter vessels in the 5000- to 20,000-psi range, the most desirable types are the shear-ring and interrupted-thread (breech block) types.

Aside from the structural requirements for an end-closure system, a most important design consideration easily overlooked is the time and labor required for removing and replacing the closure. This is a minor problem with a small vessel but it can become critical with a large vessel, particularly if a large number of short tests is planned. A fast-operating closure of the interrupted-thread type may increase the available operating time of a pressure vessel by 100% for short-term tests.

Pressure vessel orientation is another important factor to be considered. From the viewpoint of operational simplicity, economy of operating time, and safety, the vertically oriented vessel installed in a pit is most desirable. With this orientation it is not necessary to pump out the fluid before opening the vessel, and it is also possible to prefill the vessel before inserting the test object. However, some types of work, such as the testing of large-diameter objects of considerable length, may be more easily accomplished in a horizontally oriented vessel. In this case the vessel cannot be opened until the fluid is pumped out and conversely the fluid cannot be pumped in until the vessel is closed. This can be a very time-consuming procedure, particularly if the plumbing is sized for very high pressures. Other accessories for the operation of horizontal vessels are a miniature railroad-like affair for insertion and removal of test objects and a massive and somewhat complex power-driven tractor-like manipulator for end-closure insertion and removal.

A third type of installation, one which is limited as to the size of the vessel with which it can be used, is a pivoted system. An 18-in.-i.d. by 36-in.-inside-length, 20,000-psi vessel in this type of mount has been in service at one facility for four years. The utility of this type of mount has been demonstrated many times. It is particularly valuable because the closures on both ends of this vessel are removable. It is a simple operation to invert the vessel and remove the "bottom" closure for cleaning or for replacement. Some special types of instrumentation require testing in different orientations; this is easily accomplished with a pivoted vessel.

Sealing methods of various types are available. Almost without exception, pressure vessels operating in the 10,000- to 20,000-psi range utilize some type of "O" ring sealing system. This method is relatively inexpensive, easily replacable, seals well at low pressures as well as high pressures (assuming proper design), and is generally reusable for many cycles.

Pumps for high-pressure work are generally of the positive-displacement-piston type, driven either by air or an electric motor. For small volumes, of up to 100 in.^{3}/min at 10,000 psi or 50 in.^{3}/min at 20,000 psi, the air-driven pumps provide what is probably the most economical solution. For higher volume delivery requirements, particularly in the case of pressure cycling where relatively large volumes must be pumped in a short time, the electric-motor-driven pump is more advantageous.

One characteristic of air-driven pumps makes them especially attractive. They operate with a differential-area piston with a large area on one end of the piston exposed to the driving air, and a very small area on the other end exposed to the fluid to be pumped. The area ratio of air to fluid is on the order of 200 to 1. This means that the maximum output pressure of an air-driven pump can be controlled by regulating the air input pressure. Further, such air-driven pumps will automatically stall when this maximum pressure is reached and will restart automatically if the pressure on the output side drops. This in effect provides an inexpensive method of controlling the pressure in a system if the pressure tolerances of the particular pump in use are satisfactory. Electrically driven pumps, on the other hand, require a separate pressure-sensing and control system to shut down the pump when the desired pressure is reached. For purposes of estimating, the acquisition cost of pumping systems suitable to supply seawater at pressures of 15,000 psi is on the order of $5000 per gal/min at this pressure.

Pressure-cycling systems are required if an object is to be tested for its structural integrity under conditions of repeated dives or submersions. Such a system can be as simple and inexpensive as a pair of hand-operated valves to throttle the input to, and bleed from, a pressure vessel, if the number of cycles is low and the total cycling time short, or the cycling requirement occasional. It is a matter of economics and/or practicality whether manual or automatic cycling is utilized. A sophisticated automatic system would give complete control over the low-pressure dwell time, the pressure-rise rate, the high-pressure dwell time, and the pressure-drop rate. A reasonable estimating figure for such a system for vessels of 3000- to 10,000-in.^{3} capacity and 10,000- to 20,000-psi pressure capability would be on the order of $10,000 and up, depending on the cycling rate, maximum pressure, pressure-vessel volume, and bulk modulus of the entire system.

Piping, valves, fittings, and gages are components making up the plumbing system for a hydrospace simulator. There are several commercial suppliers of reliable high-pressure plumbing components. For systems that do not require the transfer of large volumes of fluids at high pressures (this applies to about 80% of the existing hydrostatic test facilities), the National Bureau of Standards (NBS) cone-type connection is the safest and most satisfactory. This type of fitting may be used throughout the whole pressure range up to 100,000 psi.

For estimating purposes, a minimum plumbing system would cost $1500 and up for the hardware. This would include several valves, a rupture-disk assembly, piping, NBS cone-type fittings, and a 16-in.-dial precision Bourdon tube pressure gage with appropriate built-in safety features.

Corrosion mitigation in a hydrospace simulation facility using seawater is a serious problem which must be given careful attention. The pressure vessel and all of its wetted parts must be given some kind of a durable protective coating such as nickel plating, a facing of corrosion resistant metal such as Monel or 316 stainless steel, or some suitable plastic coating. The parts of the vessel which might accidentally be wetted must also be protected by a protective coating. All pipes, fittings, valves, pumps, etc. must be fabricated from a corrosion resistant material such as Type 316 stainless steel. Again, the accidentally wetted components must also be corrosion resistant. One planning such a facility would do well to consult a corrosion engineer.

Corrosion not only presents a problem of damage to equipment; it also presents a secondary problem of contamination of the fluid in the system. High-pressure needle valves, check valves, and pumps are easily damaged by particulate matter, such as rust. Dissolved corrosion products may interfere with the normal seawater chemistry system one is trying to duplicate. For these reasons corrosion of the system must be reduced to a minimum and the system should ideally be of the open-loop type so that the contaminated fluid is not reintroduced into the system.

Hoisting equipment is always required in support of a pressure vessel of any size. This may be a simple chain fall on an overhead track for small lifts, or a traveling gantry-type crane for large installations. Disregarding the simple chain-hoist type, which really provides the best control for precise lifting and mating of heavy parts, the cost of the larger electrically driven types can be estimated roughly at about \$2000/ton of lift. A most important requirement for motor-powered hoists is that they be capable of operating at two hoisting rates: a rapid rate of approximately 60 in./min for general lifting of test objects and end closures and a slow rate of approximately 6 in./min for precise mating up of end closures to vessel seating surfaces, or for positioning heavy test objects in their support cradle in the vessel.

Housing for the pressure facility must provide, at a minimum, weather protection and protection from wind-blown abrasive dust. The finely machined mating surfaces of vessel and end-closure parts can be severely damaged by abrasive dust. This problem is aggravated by the fact that these parts must be both lubricated and provided with anticorrosion coatings that may also take the form of a grease or oil. Not including any structural provisions for safety barricades, a figure of about \$5.00 to \$7.00/ft^2 can be used for estimating the cost of a simple structure to house a pressure facility. If long-term testing is contemplated, the problem of air-temperature variations and the effect this has on the vessel temperature, and as a consequence the vessel's internal pressure, must be considered. A temperature change of a few degrees in the vessel can change the internal pressure by several hundred psi. For long-term tests, particularly if temperature control is to be attempted, air conditioning should be seriously considered and its cost balanced against the cost of equipment, inconvenience, and time required to circumvent air-temperature variations. Needless to say, precise instrumentation and control systems used with pressure vessels, and the tests carried on in them, will function much more satisfactorily in a constant temperature environment.

Special Problems and Some Approaches to Their Solution

Maintenance of a Realistic Seawater Environment

Seawater is much more than a simple solution of sodium chloride dissolved in water. An analysis of seawater shows that it is a complex solution containing inorganic salts, dissolved organic materials, dissolved gases, and suspended organic and inorganic materials. In addition to these constituents a great many living organisms are also present. It must also be remembered that any particular volume of sea water is in equilibrium chemically, biologically, and physically with its surrounding water mass and that the instant it is removed from its normal environment, it starts to change. When the exchange of gases with adjacent waters or the surface ceases, the temperature changes, the living organisms that were adjusted to a relatively fixed set of conditions die off and decay, and the whole system changes radically. It may be truthfully said that seawater "rots" as soon as it is removed from its natural environment. Only in a well-regulated aquarium is anything like a real sea environment preserved, and even in such an artificially maintained environment only the surface or near-surface conditions vital to certain life forms are simulated.

How then does one simulate with any degree of realism the actual deep-sea environment? Realizing that the complete simulation is beyond the present state-of-the-art, as well as most available budgets, one must eliminate the biological elements entirely and look only at the chemical and physical factors, and only such of these as appear at the moment to be pertinent to individual test requirements.

As a first step one might arrive at the following specifications for the chemical and physical properties one attempts to control for a widely applicable set of requirements. These are: salinity, dissolved oxygen, pH, Eh, alkalinity, dissolved hydrogen sulfide, dissolved free carbon dioxide, phosphate content, temperature, pressure, and anamalous trace elements. A cursory examination of this list is sufficient to indicate that these factors are not independent variables and that they are complexly interrelated. It is this fact and the fact that the end product must still look like seawater after all of these factors are adjusted to the proper values which make the control problem a most difficult one.

At the present moment a typical deep-ocean environmental simulation facility uses seawater drawn from the adjacent ocean. This water is untreated other than being filtered to eliminate particulate and gross biological matter. For most tests, salinity is considered the most important factor, and at present no attempt is made to maintain the sea water at any special set of parameters. Clean compressed air is sometimes used to aerate the water for the conduct of experiments such as those investigating the relationships between corrosion and pressure.

It is obvious from these remarks that in order to even attempt to maintain a realistic deep-sea environment in a simulated deep-hydrospace chamber, a dynamic open-loop system is required to renew the consumed chemical energy and remove the by-products of the various reactions taking place in the chamber. Such a system must be responsive to changing conditions in the chamber in order to maintain a uniform environment. A recent feasibility study indicated that the cost of an automatic system of this type would be on the order of \$500,000.

Limiting Collapse of Test Objects

In order that an analysis of the mode of failure may be made and the shock loading on the hydrospace chamber kept to a minimum, it is sometimes necessary to limit the collapse of test objects. Objects that are tested to failure will, in many cases, fail by violent implosion. One result of this is that the remains of the object are in such condition that no analysis of the mode of failure is possible.

One of the most satisfactory ways of overcoming this situation is to fill the object with some suitable fluid and then run a small-diameter, high-pressure tubing connection from the object, through the pressure-vessel end closure to the outside, with a valve and manometer attached to the low-pressure end. With this arrangement it is possible to observe the change in volume of the object as pressure is applied and thereby to observe any departure from linearity in this effect. As soon as the manometer reading indicates incipient failure, by a rapid increase in the rate of fluid displacement, the valve may be closed and the surrounding pressure in the vessel relieved. Or, if desired, collapse may be regulated by throttling the fluid being displaced from the test object. An alternative method of terminating the collapse of a slowly collapsing object is to dump the pressure in the vessel by means of a solenoid valve or an explosively actuated rupture disk.

Changes in Physical Properties of Fluids under Pressure

It is well known that the physical properties of liquids change under application of pressure. As long as tests in pressure-vessel-simulated environments are conducted using the same fluid as exists in the real environment, this factor should not pose any problems. However, if another fluid such as hydraulic oil is used in a pressure vessel in place of sea water the probability of anomalous density, viscosity, and acoustic properties influencing the test results must be considered.

Residual Pressure in Hollow Test Objects

An example of this is the bomb, or the problem presented by a hollow test object that has leaked or partially collapsed with the result that the object contains a high pressure of unknown magnitude after the test is terminated. This is not an uncommon situation and should be planned for in any test program. There are various ways of handling this situation. One is to provide the object with a high-pressure fitting and valve so that the pressure may safely be bled off after removal. The best and safest solution is to vent the object through the pressure vessel head with a length of high-pressure tubing and a valve so that the contained pressure may be bled off before opening the vessel.

Pulsation Problems with Reciprocating Pumps

Because most high-pressure pumps generate pressure with a reciprocating piston, the fluid output is delivered in pulses. As a result of this, the fluid in a vessel being pressurized with such a pump also pulsates. In most cases, this may not present any problem; however, in some tests where a smooth pressure gradient or a quiet pressure application is required, it may be intolerable. Various proprietary pulsation damping systems are available to reduce these pulsations; however, the noise transmitted through the rigid high-pressure plumbing system may, in some cases, still be a disturbing factor. One solution to this problem is the use of an accumulator system that will provide a pulse-free, relatively quiet supply of pressurized fluid to the pressure vessel.

Stored Hydrostatic Energy Problem

Potential energy is stored in high-pressure systems in three ways. One is by the compression of the fluid; this is a function of the bulk modulus, the volume, and the pressure of the fluid. The second energy storage mode is in the walls of the pressure vessel, which deform elastically as the vessel is pressurized; this is a function of the modulus of elasticity, the stress level, and volume of the pressure vessel material. The third mode is in the compressed test object itself; this is a function of its effective bulk modulus and volume. Depending on the particular requirements of an experiment, it may be desirable to have a pressure-vessel system with either a maximum or minimum possible store of hydrostatic energy.

When proof-testing an internally pressurized vessel, a situation where inherently a minimum store of hydrostatic energy is desired because the possibility of vessel failure exists, it would be well to consider the use of a high-bulk-modulus fluid such as the Phosphate-Ester-type, fire-resistant, hydraulic fluids. These fluids have far less compressibility than water and therefore store less energy at comparable pressures.

Another technique useful for reducing stored hydrostatic energy in proof-testing is as follows: A solid metal slug is made up in a size and configuration such that it fills practically the entire internal cavity of the vessel. In this way, relatively little fluid is required for pressurization and the stored energy in the compressed fluid is thereby kept to a practical minimum. Although this procedure is quite practical for small vessels, the cost of providing such slugs for large vessels would be prohibitive. For large vessels a cylinder of concrete may be cast at far less expense. The use of small metal shot may appear attractive as a means of reducing the fluid volume; however, one should note that the end product bears a striking resemblance to a large-bore cannon loaded with buckshot, with the same catastrophic potential.

There are cases where the large amount of energy stored in a compressed low-bulk-modulus fluid is most useful. One such case is in a hydraulic accumulator for operating a high-pressure cycling system. A high-pressure accumulator for this use is easily made from a 16-in., high-capacity, naval projectile. This vessel, if precharged with a low-bulk-modulus liquid or a gas, provides an effective accumulator for pressures as high as 20,000 psi.

Safety Aspects

"Safety factor," a term that appears to be subject to numerous interpretations, is determined in various ways. From the standpoint of the user, a realistic safety factor should prevent vessel failure under any likely overpressure or other probable combination of circumstances that might occur under planned operating conditions.

In toto, several pressure levels are involved in the ultimate design. One is the planned operating pressure, a second is the maximum likely over-pressure, and a third is the proof pressure to which the vessel will be subjected. The safety factor must basically be such that the vessel walls will not yield at any of these pressures.

Safety factors may be based either on the yield point or on the ultimate strength of the material used. From the user's viewpoint, it would appear more desirable to base the safety factor on the yield point rather than the ultimate strength. The reason for this is that with some alloys, such as carbon steel, where the yield point and the ultimate strength are relatively far apart, it would be quite possible, in a pressure vessel designed with a safety factor of 2 (based on ultimate strength) to exceed the yield point during a proof test. Such yielding, in a pressure vessel where close dimensional tolerances must be maintained for both mechanical fit and high-pressure seal integrity, easily could irreparably damage the vessel by jamming the end-closure locking system or upsetting the concentricity of the vessel.

The American Society of Mechanical Engineers (ASME) and other codes specify a proof-test pressure of 1.5 times the operating pressure. It would therefore appear wise to build pressure vessels with a safety factor of not less than 1.5 and preferable 2.0 (to take care of unaccounted stress raisers) based on the yield point. This is the practice with most of the large vessels presently under procurement by the government.

Operator protection is a most important and necessary consideration in the planning of a high-pressure facility. Ideally, such a facility should be designed so that all parts of the system under pressure are located behind suitable shielding or barricades so that personnel cannot be injured in the event of the failure of the vessel or any component of the system. Valves and pumps should be operated remotely and viewing should be accomplished by closed-circuit television, through properly designed massive-glass viewing windows or a mirror system. Expert advice on this subject is available from the State Industrial Safety Engineers.

The hazards involved in liquid-filled, high-pressure systems are not generally well known or appreciated by those without actual experience in this type of work. There appears to be a common belief among those who have not actually worked with large-volume hydraulic systems operating at pressures in excess of 5000 psi, that liquid-filled systems are not really hazardous, and that only gas-filled systems present any real danger in the event of failure.

Unfortunately, this is not true. Although it is true that of the two systems with the same volume and pressure, the gas-filled one will contain the greater potential energy, it does not necessarily follow that the liquid-filled, high-pressure system contains only a negligable amount of potential energy.

It is true that internal pressure in a liquid-filled vessel is more rapidly lost through a given size of opening than in the case of a similar gas-filled system. It is also true that the failure of a liquid-filled vessel would be less catastrophic than a similar gas-filled vessel. However, the operating personnel, the ones whose safety we are considering, are no less in danger of losing their lives if they are disemboweled by the violent explosion, fragments, or the shock wave of an exploding gas-filled vessel than they are from the less violent but still highly destructive fragments and high-pressure fluid from a liquid-filled vessel.

The failure of a water-filled, 59-in.-o.d. steel sphere with $1\frac{1}{2}$-in.-thick walls of 4130 steel at a pressure of 10,000 psi which is described here is typical of the tragic consequences that can occur. The vessel with a volume of about 55 ft^3 required an additional 3 ft^3 of water to be pumped into it to reach 10,000 psi. This volume change was due to the compressibility of the water plus the stretching of the metal. At the time of failure, the stored potential energy was approximately 2,000,000 ft-lb. On failure, one man was disemboweled, his head crushed and his body propelled through the air about 100 ft. Two other men near the vessel escaped with minor injuries. Many other similar accidents with liquid-filled pressure vessels are documented in the files of the Industrial Accident Investigators of California and other states. This example should serve to point up the fact that compressed liquids and stretched pressure vessels can combine to store energy of considerable magnitude, and that the mechanical failure of a high-pressure, liquid-filled system can result in catastrophic consequences.

Summary

The laboratory simulation of hydrospace is an undertaking that is difficult, expensive, and attended by a certain degree of personal hazard. The requirements of most users can be met with the presently available knowledge and hardware. Those users who require seawater chemistry control are faced with a R&D program the size of which depends on the sophistication of their requirements.

In spite of the difficulties involved and the cost of laboratory facilities, testing in a simulated environment is still far more convenient, less time-consuming, and more economical than either testing in the ocean or taking a chance on the failure of an entire system at sea due to inadequate laboratory pretesting of the components and subsystems.

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