California State University, Northridge

DESIGN, DEVELOPMENT, AND TEST OF A PRESSURIZED
DEEP SEA CREATURE CAPTURE SYSTEM

A thesis submitted in partial satisfaction of
the requirements for the degree of Master of
Science in

Engineering

by

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<td>cross-sectional area</td>
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<tr>
<td>a</td>
<td>radius</td>
</tr>
<tr>
<td>B</td>
<td>body weight of fish</td>
</tr>
<tr>
<td>C</td>
<td>constant</td>
</tr>
<tr>
<td>D,d</td>
<td>diameter</td>
</tr>
<tr>
<td>E</td>
<td>joint efficiency; also modulus of elasticity</td>
</tr>
<tr>
<td>e</td>
<td>effective fish escape path</td>
</tr>
<tr>
<td>g</td>
<td>gravity constant</td>
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<td>depth of sea water in feet</td>
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<td>l</td>
<td>length of chamber in inches</td>
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<td>moment</td>
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<td>intensity of continuous load</td>
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<td>radius</td>
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<tr>
<td>r</td>
<td>radial distance</td>
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<td>maximum allowable stress</td>
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<td>time</td>
</tr>
<tr>
<td>t</td>
<td>thickness of material</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
</tr>
<tr>
<td>V_f</td>
<td>speed of fish</td>
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<tr>
<td>V_N</td>
<td>speed of net</td>
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<tr>
<td>v</td>
<td>relative speed</td>
</tr>
<tr>
<td>W</td>
<td>deflection in inches</td>
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<tr>
<td>X_N</td>
<td>distance of fish from net</td>
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<tr>
<td>X_R</td>
<td>distance of net webbing from axis of tow</td>
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<td>x</td>
<td>distance in the x direction</td>
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LIST OF SYMBOLS

\( y \)  distance in the \( y \) direction

\( \theta \)  fish path angle

\( \nu \)  Poisson's ratio

\( \rho \)  density
ABSTRACT

DESIGN, DEVELOPMENT, AND TEST
OF A PRESSURIZED
DEEP SEA CREATURE CAPTURE SYSTEM

by
Wayne R. Tausig
Master of Science in Engineering
June, 1974

The design and construction of an experimental pressurized capture system for taking living midwater specimens down to 2275 feet is described. Results are presented, from practical demonstration, on the feasibility of such a system for catching midwater fish and providing life support during capture and afterwards in the laboratory.

The experimental unit consists of a pressure chamber mounted on the end of a trawl net. Doors on each end of the chamber automatically close and seal at the desired depth. A pressure compensator system, mounted under the chamber, automatically maintains the pressure inside the chamber at the equivalent capture depth. Windows are provided on the chamber for viewing the free-swimming specimens after the device is returned to the surface.
1. **Statement of the Problem**

The retrieval of deep ocean organisms in good physical condition for scientific study has always been a problem for the marine biologist. Current scientific study of deep ocean organisms is conducted by one of two methods.

The first method is to capture the organisms in a trawl net and to haul them to the surface. This method has several drawbacks. The rapid change in pressure and temperature usually results in severe physical damage. Organisms, saturated under the pressure of the deep sea, suffer from gas embolism when exposed to the lower pressures found on the surface. When a fish is brought to the surface, the rapid change in pressure usually results in swimbladder ejection out the mouth of the specimen. Existing trawls further complicate the problem by mangling the specimens to an unrecognizable state. This is brought about by the harsh netting material rubbing against the entrapped organisms.

The second method is to observe the organisms in their natural environment through the ports of deep submersibles. The second method is prohibitively expensive and both methods severely limit the type and extent of study.

A third method of capture is needed to aid in the retrieval of live deep ocean organisms for laboratory study and display. This method requires simulation of the physical properties found in the
deep ocean environment.

The purpose of this work was to design and develop an experimental capture system capable of entrapping specimens in a simulated deep ocean environmental chamber. Many unknowns about the retrieval of live specimens could only be resolved by experimental trials. Results obtained from testing the experimental capture system are included as recommendations toward the design of a prototype capture unit.
2. Literature Review of Pertinent Biological Aspects

2.1 Introduction

The climate of the deep sea is cold and dark, and the pressure here is so enormous it would crush anything not designed to withstand it. It abounds with nutrient minerals, yet without the energy from the sun's light, they are of little value towards sustaining life. Nevertheless, the depths of the oceans are inhabited by large varieties of fish, squid, and other creatures. Through adaptive evolution, these animals have acquired the ability to endure this seemingly intolerable climate.

Over the years, there has been much interest generated in the study of the deep sea and the creatures that inhabit it. In 1843, after completing a dredging expedition to the Aegean Sea, Edward Forbes first introduced his concept of an azoic zone.\(^1\) Before this time the popular theory was that creatures inhabited only the small region below the sea's surface. The idea of life existing at greater depths was unheard of. Deep sea fish specimens were first collected on the Challenger expedition from 1873-1876.\(^2\) In 1887, Charles Wyville Thompson, a Scottish naturalist and Chief Scientist on the Challenger expedition, wrote, "It was almost as difficult to believe that creatures comparable with those of which we have

\(^1\) Numbers in parenthesis designate references at end of report.
experience in the upper world could live at the bottom of the deep sea, as they could live in a vacuum, or in fire."

Research began soon after to learn more about the deep sea creatures. Regnard and Certes, in 1884, devised a quartz-windowed-chamber, designed to hold a pressure of 800 atmospheres, to test the effects of pressure on marine animals. Their research, reviewed in Cattel\(^3\) and Johnson\(^4\), found that small aquatic invertebrates became more active at 100 atmospheres while marine fishes were killed at pressures of 300 atmospheres.

Current studies on deep sea fish are done either on specimens brought up in a trawl net or by visual observation from submersibles and submersible television systems. In the first method the organisms are usually dead and often unrecognizable by the time they reach the surface. The second method is expensive and both methods limit the type and extent of study.

This study proposes a new method of observation, namely, to capture the fish and retrieve them to the surface at their ambient conditions. However, before an effective new capture method can be designed, it is necessary to be aware of the biological habits and the environmental influences acting upon the specimens being sought.

2.2 Description of Working Area and Ecologic Factors

It is important to define here the region of interest. Vertically, it extends from the mesopelagic to the top of the bathypelagic hydrospheres (Figure 2.1). This region, called midwater, is also known
as the "twilight zone in the ocean", (where the light is just barely able to penetrate).

Photosynthesis from the sun's energy takes place in clear water to a depth of about 100 meters. The twilight zone of just visible light extends from 150 to 1200 meters. Twilight becomes total darkness at a mean depth of 1000 meters, where physical and biological changes are much less pronounced. The 1000 meter depth is usually accepted as the division between the mesopelagic and bathypelagic faunas. N. G. Jerlov and Fritz Koczy during the oceanographic cruise of the Albatross lowered photographic plates and detected enough light for human eye stimulation down to 1800 feet. Whether fish could detect light at further depths is questionable. Clark and Kelly's measure of light in the Indian Ocean at a depth of 900 meters was found to be $6 \times 10^{-9}$ percent of the surface light. Extrapolating, they concluded that fish could possibly detect light as deep as 1300 meters.

Temperature is also considered a good measure for determining the division of ocean regions. Temperatures fall rapidly from $20^\circ$C at the surface to 4 to $8^\circ$C at 1000 meters (refer to Figure 2.1). The main thermocline is not dependent upon season. From 1000 meters to the mean depth of the ocean, 4000 meters, the temperature goes through a change of only 2-5$^\circ$C. Bruun regarded the $10^\circ$C isotherm as the dividing line between the mesopelagic thermosphere and the bathypelagic psychrosphere.

Pressure is the most dominant physical feature at these depths. At 1000 meters for instance, the pressure is over 100 times normal
FIGURE 2.1  OCEAN REGIONS  (From Ref. 11)
atmospheric pressure. In the deepest part of the ocean it exceeds $3\frac{1}{4}$ tons per square inch.

2.3 **Definition of Species**

Due largely to their harsh environment, most midwater fish grow to a length of only six inches or less. Representatives of individual species show a remarkable change in their physical features between the mesopelagic and bathypelagic regions. Fitch\(^9\) describes different species of mesopelagic and bathypelagic fish.

The principal mesopelagic fish generally considered by ichthyologists include the lantern fish (myctophidae), the hatchet fish, the bristle-mouth cyclothone, and the giant swallower (Refer to Figure 2.2). Since these fish live in the twilight region (200 to 1000 meters), they are still able to gather what light there is available for useful purposes. As a result, the midwater mesopelagic fish have extremely enlarged eyes in proportion to their bodies.\(^5\)

The coloring of the hatchet and lantern fishes, with dark backs and silvery sides, are representative of the mesopelagic species. Denton and Nicol\(^10\) have theorized that in order for a fish living in the threshold of light to be perfectly camouflaged, an observer should see the same amount of light when the fish is present as when it is not. The strong downgoing light is reflected off the dark back of the fish just enough to match the weak upgoing ambient light. The silvery sides should reflect the background in all directions. This type of fish would normally be vulnerable from below where predators could look up
a) LANTERN FISH

b) HATCHET FISH

c) BRISTLE-MOUTH CYCLOTHONE

d) GIANT SWALLOWER

FIGURE 2.2 MESOPELAGIC FISH
and see their silhouettes. However, they have developed light organs, called photophores, to fill in their silhouettes with artificial light, and match the background light from above. Photophores are discussed in section 2.4.

The bathypelagic species which include anglers, dragonfish, viperfish, and gulper eels are totally different (Refer to Figure 2.3). These fish live below the light threshold. As a result, their eyes are minute in proportion to their body size, and their skin pigment is either black or dark brown. These predators, who have no scales or silvery sides, enjoy the cover of darkness.

The larval life of both species is spent at the sea's surface. The eggs are shed at depth and develop as they rise. This way the young are spread out over immense areas of the ocean. In general, the fins of the midwater fish are poorly developed. Since their defense is mostly by camouflage, and their prey attracted to them with luring lights, there is little need for speed.

2.4 Photophores

Due to the absence of sunlight at depth, both mesopelagic and bathypelagic fish have developed the ability to create their own light in the form of photophores. Photophores are small biological luminous buttons, or light organs, along the front and sides of the fish. Nearly two-thirds of the species of midwater fish have light organs. Clarke and Backus lowered photomultiplier tubes into the ocean to measure light from luminescent animals. They detected organisms to a
a) ANGLER

b) DRAGON FISH

c) VIPER FISH

d) GULPER EEL

FIGURE 2.3 BATHYPELAGIC FISH
depth of 3,750 meters. The highest density of living light was found at 800 meters.

C. P. Idyll\(^{6}\) describes the luminescent organs. Their structure very closely resembles eyes, since organs receiving and reflecting light need focusing lenses, tissue reflectors, light producing cells, a diaphragm to control the amount of light emitted, and color cells to give a hue to the organ. The most widely accepted theory is that light is emitted by bacteria in the cell, and the flow of blood to this cell controls the intensity. The most common luminous colors from fish are blue-green, yellow-green, red and white.

Fraser\(^{13}\) and Clarke\(^{14}\) have suggested that one function of the ventral photophores is to break-up the silhouettes of the fish and prevent them from being spotted by predators lurking below. N. B. Marshall\(^{5}\) reported that photophores may be a means of identification for the species. Each sex bears its own luminescent sign.

Another popular theory is that light of some photophores located on an illicia (or lure), and near the mouths is used by certain species to attract their prey. The stomialoids (dragon fish, viperfish) have chin barbels and dorsal rays with light organs on the ends. These may be held in front of the mouth so that the lighted tip acts as a lure to draw in its prey. Marshall writes, "Deeper angler fishes have yet to be seen taking their prey, but it seems certain they took to angling millions of years before man."\(^{11}\)
2.5 **Swimbladders**

Swimbladders are found in most species of fish that swim and hover. The purpose of the swimbladder is to keep the fish weightless and enable it to conserve energy. Denton and Marshall\(^{15}\) found that a fish deprived of its swimbladder must "treadwater" with a force equal to five percent of its weight in air.

The buoyancy is supplied by carbon monoxide gas which is secreted into the swimbladder from an enzyme system in the cells of the gas gland.\(^{16}\)

A fish must adjust its buoyancy on a dive or ascent in proportion to the change in ambient pressure. Fish requiring smaller swim bladders can change their displaced volume faster and thus change their buoyancy more efficiently. In numerous mesopelagic fish the swimbladder is regressed. Bathypelagic fish have lost their swimbladders entirely. These fish have adapted to neutral buoyancy by reduced skeletal and muscular systems. Fish with swimbladders have been taken down to depths of 7,160 meters where the gas has a specific gravity of 0.7.\(^{17}\) Swimbladders would supply zero lift below 8,000 meters.

Midwater fish with swimbladders can adjust the pressure in the bladder with ambient pressures under normal ascent. However, when a fish is snatched to the surface, as when pulled up in a trawl, the internal gas pressure swells the bladder until it is ejected like a balloon out the mouth of the victim.

An interesting subject currently under study is the ability
of these fish to maintain gas tensions between the swimbladder at ambient pressures, and the blood at one atmosphere pressure. Scholander\(^{(18)}\) has shown that this is done in the retia mirabilia, which circulates blood to the gas gland of the swimbladder. Marshall\(^{(19)}(20)\) has found a direct correlation in the length of the retia to the depth (i.e., pressure) at which the species is found. The pressure gradient becomes steeper as the depth is increased, and thus the more efficient the gas exchange must be. As the length of capillaries increases, the diffusion surface will increase causing a more efficient gas exchange. Therefore, the length of the retial capillaries increases in direct proportion to the depth range of the fish.

The ability of certain midwater species to migrate to the surface is discussed in section 2.7.

2.6 Lateral Line System

The lateral line system consists of delicate organs along the sides of fish sensitive to low-frequency vibrations. The nerves are stimulated by small currents signaling the fish that there is something moving nearby, whether it be prey, enemy, mate, or an approaching trawl net. The lateral line system is well reviewed in Dijkgraaf.\(^{(21)}\)

2.7 Habits of Midwater Fish

Diverse mesopelagic fishes spend both their larval life and much of their adult night life near the surface while bathypelagic fish
spend only their larval life at the surface. At night some mesopelagic species make diurnal migrations to the surface to feed on plankton. There is, however, no evidence that these fish migrate to spawn. Pearcy and Laurs(22) found migration occurring above 500 meters. There is no evidence showing upward migration between 500 and 1000 meters.

One scattering layer of fish observed by Blaxter and Currie(2) rose 100 meters in twenty minutes during a cloud cover. Lantern fish have been known to migrate in one hour from 50 atmospheres and $10^0C$ to one atmosphere and $20^0C$. Marshall writes, "Relevant tests on what pressure changes these fish can withstand should be undertaken."

Not only must these migrants withstand pressure changes; they must withstand temperature changes too. Between latitudes of $40^0N$ and $40^0S$, fish migrating from 400 meters will undergo a warmer temperature change of 5 to $10^0C$ by the time they reach the surface. Such changes would harm many shallow-water species. McLaren(23) has hypothesized that resting in cold water and migrating to warmer waters to feed at night will gain an "energy bonus".

Marshall writes, "Diverse marine organisms, from bacteria to fishes, can tolerate a wide range of hydrostatic pressure so long as ambient temperatures are at or near their optimum requirements. It ought to be feasible then, to keep some deep sea animals in the laboratory, so long as they are kept at temperatures near that of their living space."

Baker(24) has shown this. Using an Isaacs-Kidd Midwater
Trawl, he was able to keep the organisms listed in Table 1 alive in a tank chilled to 7-10°C.

<table>
<thead>
<tr>
<th>Species</th>
<th>Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spirila</td>
<td>8 days</td>
</tr>
<tr>
<td>Acanthephyra</td>
<td>18 days</td>
</tr>
<tr>
<td>Gigantocypris mulleri</td>
<td>13 days</td>
</tr>
<tr>
<td>Oplophorus</td>
<td>31 days</td>
</tr>
</tbody>
</table>

Foxton(25) kept deep sea prawns caught at 400 meters alive for 20 days in an aquarium chilled to 7-8°C. The larva hatched from their eggs.

On capture methods, Marshall suggests attaching a thermally insulated bucket to the end of a trawl net. The net should be made of buffering material and towed at slow speeds to protect the species' delicate skin. The aquarium should be lit dimly since these species are inactive by day.

Most midwater fish are predators rather than scavengers, since by the time any dead or surface food sinks to these depths, most of the nutritional value is lost to bacteria. The food of these species is made up of young fish, euphausiids, arrow-worms, and copepods. Judging from their poorly developed swim fins, most fish lure their prey rather than hunt it.

2.8 Concluding Remarks

The research has shown that deep sea fish have been able to adapt to their harsh environment. Due to the scarcity of food and nutrition, the population density of the fish is kept small. However, in order for individual species to keep in touch for mating purposes,
they have developed light organs as a means of identification. To conserve energy, most species attract their prey to themselves rather than hunt it. To avoid being eaten, they have resorted to camouflage, rather than speed as a means of defense. To ensure survival of the species, larva develop and rise to the surface where they are spread out over vast regions of the ocean.

Although they survive in a harsh environment, midwater fish are very delicate to handle. Current methods of capture (i.e. trawls) totally mutilate the specimens. It is feasible, however, to design a new capture system and to keep the specimens alive for protracted periods of time.

Some of the pertinent questions asked by experts are:

1. "How do deep sea fish secrete gasses into the swim bladder against the high pressures?" (6)
2. Lantern fish have been known to correct swimbladder pressures from 165 feet to 1600 feet in two hours. "How can they transfer pressure in the gas bladder as they ascend and descend?" (5)

The general problems with research in the field of deep sea biology and ichthyology are numerous. The analysis of live laboratory specimens is basic to all future research.

A device which can capture midwater fish at their normal pressure and temperature, and maintain these conditions as the device is raised and subsequently used in the laboratory, would increase the opportunity to investigate some of these questions.
3. Literature Review of Previous Work on Retrieving Deep Ocean Organisms

3.1 Introduction

Due largely to sampling difficulties, little is known about the biology of midwater fish. Supplementary data from line fishing and photographic observations have been helpful. The first deep sea angler fish, for instance, caught in 1873 on the voyage of the Challenger, is still considered a rare catch today. (6) Sophisticated flash photography (made to trigger by the pull of a baited hook, or by the interruption of an infrared beam, or echo sounder) has been somewhat successful in supplying data. However, additional information about the biology of these fish cannot be obtained until a better method of capture is devised.

Over the years many different devices for capturing deep ocean organisms have been tried, including traps, hooks, bottles, samplers, grabs, and nets. However, through experience it has been found that no one net or method is satisfactory for catching all types and all sizes of organisms. (26)

This research study is mainly concerned with the different capture methods and devices used to date. It has been stressed throughout the literature that an instrument or device lowered over the side of a ship will sooner or later be lost. Therefore, devices must be built as cheaply as possible while retaining the highest possible reliability. (27)
3.2 Nets and Trawls

Trawling with nets is probably the most widely used method for catching fish and plankton. Nets are classified into two categories depending on whether they are pulled vertically or horizontally through the water.

Vertical nets are lowered straight down over the side of a stationary ship to the desired depth, where they are then raised slowly by winch through the vertical water column above. Small plants and very small animals have successfully been caught in 50 centimeter ring nets (200 meshes per inch). Fish, one centimeter in length, have been caught in similar nets with a net mouth of one square meter. Larger openings, however, become too cumbersome for the vertical trawl. For this reason, vertical nets are mostly limited to the capture of plankton.

Horizontal ring nets for larger animals have openings up to 113 centimeters (larger sizes are too cumbersome).

The "standard" horizontal trawl consists of a fairly large net and depressor (or paravane) which is towed behind a boat. The function of the depressor is to keep a downward force on the bottom of the net opening such that the entire net assembly remains at the desired towing depth. Kyle's Midwater Umbrella-Trawl \(^{(28)}\) and the Isaacs-Kidd Midwater Trawl \(^{(29)}\) are good examples of currently used nets.

The opening of the Isaacs-Kidd Midwater Trawl (IKMT) (Figure 3.1), is supported by a large six or ten-foot V-shaped depressor plate, bar, and bridles. The net can be towed to speeds up to
FIGURE 3.1 ISAACS-KIDD MIDWATER TRAWL
six knots. However, two knots is considered to be the fastest recommended towing speed, since greater speeds damage fish by pressing them hard against the mesh. The briddles tend to obstruct the mouth of the net and the depressor acts to scare the fish away.

The Rectangular Midwater Trawl has rectangular openings in 1, 8, and 90 square meter sizes. The bottom half of the opening is weighted to force it open. In its towing configuration, the mouth of this net is never truly open due to the drag force acting on the weights (Figure 3.2).

Prince Albert I of Monaco used even larger nets, developed for the commercial herring industry, for oceanographic research. Bouree\(^{(30)}\) designed a 15-meter square mouth net for horizontal operation. To control its depth, his net was lowered vertically; towed for five minutes; stopped; lowered again; towed for five minutes; etc. Larger trawl nets, which are held open by otter boards, floats, and weights are all difficult to operate.\(^{(31)}\) Heligoland's three-otter-board-net, reviewed in Heincke\(^{(32)}\) had a triangular mouth of 50 to 100 square meters. The Larsen Trawl (the largest found in the literature review) was so large (a 300 square meter opening) it had to be strung and towed between two ships.

Nets are by no means the only solution to sampling deep sea specimens. They have many drawbacks. Many animals can sense the approach of a net (fast ones avoid it). Different species vary in net-avoiding skills. In this sense, nets become "species selectors". Their contents do not represent a true picture of what species exist
FIGURE 3.2  RECTANGULAR MIDWATER TRAWL
at trawl depths. Some fish find their way out once they have been trapped. Fine-mesh nets catch small organisms but produce high drag. Therefore, they must be towed slowly. Small or large nets towed slowly do not catch large animals. Large-mesh nets may be towed faster but the smaller fish escape through the mesh. The IKMT towed at three knots will sample cyclothone but is too slow for myctophidae. (Hersey and Backus\(^{(33)}\) recorded ascent speeds of the myctophidae to be 0.125 meters per second at a depth of 500 meters). The same IKMT towed at higher speeds caused damage to the specimens.

Netting material is coarse. As the fish are swept along the net, their skin and scales get stripped off. Some specimens become so badly damaged they are unrecognizable. Towards the end of the net, the specimens become overcrowded and crushed.

On sampling, M. R. Clarke writes, "Sampling animals in the deep sea has been likened to sampling from a helicopter, in the dark, two miles high, towing nets or hooks on or near the ground. Any samples would provide a poor picture of terrestrial life!"\(^{(27)}\)

Barkley\(^{(34)}\) has worked out a theoretical formula to predict fish avoidance. Figure 3.3 shows a diagram of the escape path.
FIGURE 3.3 ESCAPE ANGLE (From Ref. 34)

Where:

\[ \begin{align*}
V_{N} &= \text{speed of the net in excess of } V_{f} \\
V_{f} &= \text{speed of the fish at } f \\
y &= \text{distance of fish to axis of net's path} \\
\theta &= \text{angle of divergence between fish's path and net's path} \\
X_{N} &= \text{distance of fish from net} \\
X_{R} &= \text{distance of webbing from axis} \\
T_{0} &= \text{time at which fish perceives net} \\
T_{1} &= \text{time at which net passes fish} \\
e &= \text{effective escape distance}
\end{align*} \]
At time $T_1$, 

$$e = (T_1 - T_0)V_f \sin \theta + y$$

If $e$ is greater than $X_R$, then the fish has avoided the net.
If $e$ is less than $X_R$, the fish is caught.

For a fish with $V_f \approx V_N$, $e$ becomes of great importance since $e = f(\sin \theta)$. Since it is desired to have $e$ small, it is best to design a net to minimize the time between when the fish first perceives the net to when the net passes the fish (i.e., minimize $(T_1 - T_0)$).

Avoidance may be enhanced due to the fish's lateral line sensing pressure waves. Larger depressor vanes or otter-boards, and higher towing speeds cause higher towing resistance which propagates higher pressure waves. These waves act as a siren to warn the fish of an approaching trawl.

The Hansen Vertical Net (Figure 3.4) reduces the water pressure and drag by reducing the opening relative to the filtering surface. The conical non-filtering portion is added to the upper part and fastened to a smaller ring and stiffened by supporting rods.

The way in which a net is attached to the tow line may also affect $(T_1 - T_0)$. Figure 3.5(a) shows a typical ring-net with the bridle tied off in front of the net. The bridle acts to ward off the fish long before the net reaches them. In Figure 3.5(b), the bridle has been replaced with a pivot to avoid scaring the fish.

The need for knowing the depth at which animals are caught has lead to the invention of net opening-closing devices. If a sample
FIGURE 3.4  HANSEN VERTICAL PLANKTON TOW
Figure 3.5 Ring Net/Cable Connections

(a) Bridle

(b) Pivot
is required from a discrete scattering layer, it is necessary to prevent contamination while the net is being lowered or raised. It is desirable to have the net closed until it reaches the desired depth. The net is then opened by a signal (messenger, accoustical, pressure switch, timed switch, or depth pinger) for the duration of the trawl. Finally, the net is closed for the ascent back to the research vessel.

The use of closing devices began as early as 1888, when Chun (35) devised a propeller-turned rod (driven by the water flowing through it) to open and close his net. Before the voyage of the Challenger, marine biologists believed that animal life was confined to the water layer just beneath the surface. It was Chun's net which proved the existence of mesopelagic fish.

Many attempts to design simpler open-closing devices followed. Hoyle, (36) in 1889, used a lead messenger sent down the cable to close his vertical net. Nansen (37) describes his closing principle which is still widely used today. Marr (38) first used a messenger to close his horizontal tow. Motoda (39) describes an apparatus with rotating buckets. Aron et.al. (40) gives details of a bucket with internal shutters that can be closed successively by means of signals sent down a multicore armoured towing cable.

The best method in use today utilizes pressure switches which dispenses with control cables and messengers. Bé (41) describes a pressure sensitive sampler with three nets hinged across a square opening. Each net closes as the following set of nets is unfolded. An adaptation of Bé's sampler with a closing device is described by
Pearcy and Hubbard\textsuperscript{(42)} Foxton\textsuperscript{(43)} used pressure switches to operate his "catch dividing bucket" (CDB), in which flaps control the passage of organisms into one of two ducts in a "Y" shaped aluminum bucket.

The Clarke-Bumpus plankton net\textsuperscript{(44)} shown in Figure 3.6(a), has been used successfully for obtaining plankton specimens. It consists of a brass tube with a net mounted on one end and pivoted to a metal frame on the other. The pivot allows the tube to turn horizontally when towed. Thus, the net always takes a horizontal position regardless of cable angle. Two metal planes mounted on the sides of the tube keep the instrument hydrodynamically stable.

The frame is attached to the towing cable by a loosely fitting spring pin and gate lock. The frame is then free to swivel around the cable so that during towing, the opening of the tube is always directed forward (Figure 3.6(b)). A butterfly valve (or circular disc shutter) mounted in the mouth of the tube, is pivoted to rotate about a vertical plane. The valve is set closed on descent. At the desired time, a messenger is sent down the cable and triggers the turning of the valve 90 degrees. At the end of the trawl, a second messenger turns the valve another 90 degrees. A flowmeter is mounted inside the tube which registers the volume of water entering the net during its slow speed tow.

3.3 \textbf{Plankton Samplers}

Fine-mesh plankton nets towed horizontally behind a slow moving vessel have been used successfully for many years. However,
FIGURE 3.6 THE CLARKE-BUMPUS PLANKTON NET (From Ref. 44)
taking samples over large areas of the ocean in this manner becomes time consuming and awkward. New designs have increased plankton tow efficiency by enclosing the plankton nets inside of streamlined "torpedoes". These high-speed samplers can then be towed at normal cruising speeds while the vessel is enroute from one station to another without interfering with its progress.

The Hardy Continuous Plankton Recorder\[45\] was designed to map the distribution of plankton while being towed. Figure 3.7(a) shows how a roll of gauze is stretched between two spools across the mouth of the net trapping the plankton as they enter. While the recorder is towed through the water, a propeller drives the gauze spools such that the density and distribution of plankton specimens are "suspended" on the gauze roll for future study. Guard rails have been added to the propellers in later models to keep the seaweed and fish from clogging it. Inclined diving planes supported by brackets located below and towards the front ensure that, with a given length of towing warp, the instrument will tow at a constant depth despite changes in the ship's speed (changes of 8 to 16 knots will not affect the towing level of the recorder). Shock absorbers are used to fasten the cable to the unit and prevent cable fatigue. Two small horizontal fins and one large vertical tail fin keep the unit hydrodynamically stable while being towed. Altogether, the Continuous Plankton Recorder weighs 156 pounds.

The High Speed Hardy Indicator\[46\] shown in Figure 3.7(b), utilizes a large net surface in relation to the opening. This reduces
(a) HARDY CONTINUOUS PLANKTON RECORDER  
(From Ref. 45)

(b) HIGH-SPEED HARDY INDICATOR  
(From Ref. 46)

FIGURE 3.7 PLANKTON SAMPLERS
back pressure so that the specimens are not crushed. The whole assembly is fitted into a torpedo-shaped body for high-speed tow.

A newer generation net called The Jet Net\(^\text{(47)(48)}\) has successfully been tested at speeds of 18.5 knots without any specimen damage. In past design considerations, as the design speed of the sampler was increased, the mouth opening was reduced to keep the back pressure and internal flow small. However, a small opening negates the advantage of higher speeds. The Jet Net, shown in Figure 3.8, is an encased net which contains expanding then contracting cross-sections for the purpose of slowing the flow down to minimize specimen damage. The velocity inside the net chamber becomes 6.4 times less than its tow speed.

It was found that in order to minimize turbulent flow losses, the inclined angle of intake must be less than \(7^\circ\). The intake and exhaust openings are designed so that water velocity entering and leaving the sampler are the same as its tow speed. Due to internal losses, the exhaust port is slightly larger than the intake. Depth control and stability of The Jet Net are accomplished by using a standard Isaacs-Kidd depressor.

A plankton counter, described in Herring et al.\(^\text{(27)}\) records plankton density electronically. As the organisms pass through a tube, they change the impedance between electrodes and are counted. In this instrument, the impedance is taken as being proportional to the volume of organisms.

Schubel and Schiemer\(^\text{(49)}\) describe a device which freezes a
FIGURE 3.8 THE JET NET (From Ref. 47)
thin layer of water entrapping all suspended particles in it for an undisturbed sample. The sampler, shown in Figure 3.9, consists of a 16-ounce stainless-steel thermos bottle, stopper, rod assembly, and solenoid triggering mechanism. The thermos bottle is partially filled with dry-ice chips and acetone. An aluminum post conducts the cold to the sampling disc. As the solenoid is activated, a rubber pad is raised from the disc allowing water to enter and freeze. Two seconds later, the solenoid drops the pad, stopping further freezing. The sample is then returned to the lab for microscopic study of the suspended organisms. All seals used in this device are coated with antifreeze.

3.4 **Free Vehicles**

A free vehicle consists of a weighted ballast, an oceanographic instrument package and a floatation device. As the name implies, a free vehicle is in no way attached to the ship. It performs the function of transporting the oceanographic devices to the depths of the ocean, returning them to the surface, and providing a means of recovery. The lead or steel ballasted vehicle is initially dropped over the side of the vessel where it free-falls to the bottom. After some time, a release mechanism releases the ballast and the vehicle rises back to the surface. Buoyancy for the return trip to the surface is supplied by floats of syntactic foam or gasoline. Instrument packages transported by free vehicles include bottom traps, sediment traps, current recorders, and deep sea camera systems.
Figure 3.9 *In-Situ Water Sampler* (From Ref. 49)
Recovery is assisted by radar, transmitter/receiver, or blinking lights. Figure 3.10 shows a typical free vehicle system.

Buoyancy float materials include glass spheres, syntactic foams, and gasoline. Glass spheres, reviewed in Knauss\(^{50}\) and Raymond\(^{51}\) are fairly expensive (about $30-$50 per five gallon float) and have pressure limits. Syntactic foams, reviewed in Shick \textit{et al.}\(^{52}\) are prohibitively expensive. Five gallon buoys filled with gasoline are inexpensive (about $12 per float) and provide 5.2 kg of floatation. However, gasoline is extremely flammable and caution must be used when handling it aboard ship. Humble Oil manufactures Isopar-M, a lightweight vehicle oil, which provides 5 kg of buoyancy per five gallons, and is less flammable than gasoline.

Invention of the release mechanism permitted the development of free vehicles. However, more sophisticated releases are still desired. Release trips include magnesium releases, pressure releases, bottom contact releases, magnaelectric releases, solenoid releases, timers, and accoustic command releases.

Magnesium releases, reviewed in VanDorn\(^{53}\) are the most commonly used. They consist of a piece of magnesium fabricated into a weak link in contact with another metal (usually steel). The contact of the dissimilar metals in sea water causes rapid corrosion of the magnesium until the link can no longer support the load. Release time becomes a function of magnesium diameter. A simplified magnesium release along with a release time curve is shown in Figure 3.11. Magnesium releases are suitable for release times of 4 to 70 hours.
FIGURE 3.10 FREE VEHICLE
FIGURE 3.11 MAGNESIUM RELEASE (From Ref. 53)
They are simple, cheap, reliable, but unpredictable. Improved versions are predictable to one hour within a 20-hour range. Schrader\(^{(54)}\) has experimented with cascading magnesium pins for the purpose of extending the release time.

The wire-plier release, shown in Figure 3.12, uses a 0.15 centimeter magnesium wire. The handles of the pliers act as electron acceptors, necessary in all magnesium releases. Phleger et al.\(^{(55)}\) have found release times of this device to be about six hours. For lesser times, Phleger and Soutar\(^{(56)}\) have tied hook lines between candy lifesavers. The candy lasts about 10 minutes in shallow water (75 meters or less).

Figure 3.13 shows a pressure release which uses commercially available rupture discs. They can be preset to release at a depth of ± two percent.\(^{(57)}(58)\) The magnalectric release (electromechanical) is activated by a 1\(\frac{1}{2}\) volt 50 ma DC signal. This device has proven unreliable in prolonged exposure to deep cold water and has been abandoned in favor of the simpler magnesium release.

Bottom contact releases are used on free vehicles that descend to the sea floor. When a spring arm comes in contact with the bottom, the release mechanism triggers. The tension of release must be finely adjusted so that it is unable to release under the combined force of drag and buoyancy during free-fall.

The acoustical recall release, the newest release on the market, appears to be the most reliable. Field tests on the acoustical command and control system, manufactured by Inter Ocean Systems, Inc.,
FIGURE 3.12 WIRE-PLIER RELEASE
FIGURE 3.13 PRESSURE RELEASE (From Ref. 57)
San Diego, show 100% release performance at a depth of 1500 meters.

The free vehicle has been utilized in the retrieval of deep sea specimens by transporting to the bottom and back a Benthic Trap. The Benthic Trap is shown in Figure 3.14. It essentially consists of a baited "lobster-type" trap set on the bottom. Crawling creatures can enter the lower cone and fish enter the upper cone. Schick et. al. (52) have used the Benthic Trap down to depths of 2800 fathoms. Bottom periods of four to ten hours prior to releasing to the surface were found to be the most productive. One of the problems encountered with this device is determining whether all the creatures caught actually came from the bottom or whether they entered the trap while the free vehicle was descending or ascending. Daniel M. Brown, Scripps Institution of Oceanography, is currently working on a Benthic Trap with opening and closing doors. Phleger et. al. (55) have been successful in catching sablefish with plastic elliptical lobster traps assembled on a free vehicle in the same manner as the Benthic Trap.

George B. Schick, Senior Engineer; John D. Isaacs, Professor of Oceanography, Director of Marine Life Research, and Meredith H. Sessions, Associate Engineer; working together at Scripps Institution of Oceanography, have concluded about the retrieval of deep sea specimens in the Benthic Trap:

"The higher forms of marine life with swim bladders are generally killed by gas embolism during ascent. Many of the fish and invertebrates, however, survive the pressure change and are caught alive but die soon afterwards - probably, due to temperature change. These could undoubtedly be kept alive for further study if refrigerated aquaria were available. We have done some design work on a pressurized
FIGURE 3.14 BENTHIC TRAP
trap which would preserve all specimens alive for further study, but there seems to be a lack of interest in such study among biologists. There is some experience to indicate that fish can survive depressurization, if it is carried out very slowly, and adapt to a lower pressure environment. (52)

3.5 Other Capture Methods

Alternate methods of obtaining deep sea fish include night fishing, line fishing, and even fishing with some pretty unusual types of apparatus. Biologists have found good specimens of mesopelagic fish inside the stomachs of tuna and albacore. They use weighted lines to catch the tuna and albacore at night as they feed on the deep sea fish. Some of the migrating species of fish are attracted to bright lights at night and can be plucked from the surface in small hand nets.

Dr. James Westphal, California Institute of Technology (59), has experimented with high pressure aquaria containing deep sea invertebrates. To retrieve specimens for the aquaria, he used standard bottom grabs. He found that specimens near the outer edge of the grab were killed on the ascent, probably due to temperature change. However, he was able to secure live specimens from the center part of the mud grab, which acted to insulate them.

Large pumps have been used with little success. In this method, a large and cumbersome hose is lowered to the depths of the ocean where specimens are sucked up back to the vessel. Most animals are mutilated in this process.

Larger "unexpected" creatures of the deep are known to exist
but no capture method has yet been tried. Under development at Scripps is the Monster Trap, shown in Figure 3.15. The Monster Trap is sent down on a free vehicle with three large barbed jaws in the closed position. As the trap descends, the sea pressure acts on a piston to open the jaws exposing a baited lure. When a monster of sufficient size attacks the bait, a toggle valve on the bait admits sea pressure to the other side of the piston, slamming the jaws shut. This action releases the ballast weight and the vehicle returns to the surface for recovery. (52)

3.6  Concluding Remarks

It is clear that no single capture device or method is satisfactory for catching all types and sizes of specimens. Capture devices should be designed specifically for the species desired. Size, speed, and sensing capabilities of the fish all have to be taken into account. A thorough understanding of the habits and capabilities of the desired species is important so that the best features of past and present designs may be utilized in the new capture system.

A pressurized capture system may not have aroused much interest in 1968. However, from the response of biologists today, this author believes that there is definitely a need for such a device to further the study of live deep sea specimens.

Time and time again the literature states that "there is reason to believe" that deep sea fish could be decompressed over a period of time and could adapt to atmospheric pressure. A new high
FIGURE 3.15 MONSTER TRAP (From Ref. 52)
pressure capture system could be used to prove or disprove this theory. This author has not found any evidence to show that this has actually been tried. The reason seems to be that there is no existing apparatus capable of such an experiment.

The high pressure capture of deep sea fish is an exciting new field waiting to be explored.
4. **Project Goals**

The goal of this thesis work is to research, design, and construct an experimental self-contained capture/aquarium unit capable of bringing deep ocean organisms up from depths of 2,000 feet and providing life support in the form of environmental simulation.

The results obtained from the experimental unit will be used to suggest recommendations for a prototype capture/aquarium unit capable of bringing deep ocean life up from depths of 1,000 meters, and providing continued life support for protracted periods of time.

By successful completion of these goals, it is hoped that continued work and refinement on the deep ocean capture system would produce a desirable oceanographic instrument, extending man's abilities for observation, analysis, and control.
5. Experimental Capture Chamber Design

5.1 Introduction

The initial version of the midwater capture system consists of a compression chamber mounted on the end of an Isaacs-Kidd Midwater Trawl. The compression chamber is designed to operate at an ocean depth of 2000 feet. Its function is to simulate deep water by maintaining hydrostatic pressure during the recovery operation and afterwards in the laboratory. Deep water specimens, funneled through the net into the chamber during the trawling operation, are studied through viewing ports mounted in the sides of the chamber.

In the laboratory, specimens are either maintained in the self-contained compression chamber unit, or transferred into a different pressurized aquarium unit. A pressurized aquarium system is discussed in Appendix A.

5.2 General Arrangement

The original concept of catching deep water fish in a compression chamber was to use either a stationary baited trap, or a trawl net arrangement. Because it was felt that there was a greater probability for catching the fish in a net, the latter arrangement was chosen.

The chamber is mounted at the trailing end of a standard Isaacs-Kidd Midwater Trawl. A paravane, located between the net mouth and tow line, maintains the net at its proper tow depth.

The basic configuration for the specimen compression chamber consists of a pressure vessel containing a volume of seawater. Fins
are provided on the sides of the chamber to keep it stable during tow. Gas pressure inside the chamber is used to cushion the water, maintain constant hydrostatic pressure, and simulate depth. The gas source is a separate tank unit, called the pressure compensator, mounted under the belly of the chamber. A partition separates the gas from the water in order to prevent the gas from dissolving into the solution.

Doors at each end of the chamber are held open during the tow to allow the water to flow through. A small inner-net, mounted at the center of the chamber perpendicular to the flow, entraps the small specimens inside. Upon completing the towing operation, the doors are triggered externally to shut and seal pressure tight. Triggering the doors is accomplished by a pressure switch, a time switch, or a combination of the two. The capture unit is then hauled to the surface where the specimens can be viewed through side-mounted acrylic windows. Figure 5.1 shows the general arrangement for the capture system.

5.3 The Need for an Experimental Apparatus

Questions of whether deep water fish can be taken alive and whether they can be decompressed or not are the main factors in the decision to go ahead with a serious design for an experimental unit. Review of literature suggests decompression of fish is possible. However, there is no experimental evidence to prove this.

It is not the intent of this thesis to provide biological data on actual live specimens. The intent here, is to design an experimental apparatus capable of providing information on the feasibility of
live specimen capture.

The design and construction described herein is primarily concerned with the pressure chamber itself. It is recognized and noted that, in the design of the experimental unit, certain problems, such as the damaging effect on specimens by the long net (Refer to Section 3.2), and dissolved gasses in the chamber, are neglected.

The experimental unit is designed to provide life support for a limited time only. In this manner, weight and material cost are minimized while still providing for a useful experimental apparatus.

5.4 Evolution of the Basic Design Configuration

As a result of trade-off analysis, six design studies were considered before the final design was chosen. Mounting the chamber on the end of the trawl net required that its weight be kept to a minimum. Chamber shell, end plates, and quick actuating doors were of prime consideration.

The first two designs in the pattern of development are shown in Figure 5.2. Design 1 consists of a six-inch steel tube with externally threaded heads on each end. The heads, sealed with double circumferential O-ring seals, contain the hinged door assemblies. The interchangeable head and door assemblies may be removed for modifications. The doors, triggered externally through the cylinder shell, seal against the O-ring face seals by spring hinges. A net retainer located on the front head, provides for attachment to the trawl net and later to the transfer lock.
FIGURE 5.2 DESIGN DEVELOPMENT

(a) Design 1

(b) Design 2
Many problems are inherent in Design 1. External threads on the heads become very tight and bind on large diameter openings. While the chamber is being subjected to varying temperature and pressure environments, expansion and contraction of the vessel shell can cause leakage through the circumferential seals. The use of face-type seals is preferred.

Another problem is that hinge springs cannot provide enough sealing force for the doors. Outside penetrations through the shell should be avoided, and the number of seals minimized in order to minimize possible leak paths. The hinge pivot together with a flat-faced door becomes a critical alignment problem.

Design 2 incorporates external flanged heads in conjunction with a six-inch seamless tube. The bolted flange design has the advantage of using the more reliable face seal. However, external flanges of this type become prohibitively heavy (on the order of 100 pounds per flange).

Concurrent studies on quick actuating doors made it evident that this component would become one of the major problems in the chamber design. Successful pressurization at depth would depend entirely on the initial seal made by these two doors. Figure 5.3 shows some of the different doors considered.

Design 3, shown in Figure 5.4, consists of an eight-inch nominal schedule 80 steel pipe with an internal-screwed-type head. By machining down the center part of the shell, the total weight is reduced by 27.7 pounds. The new closing door mechanism consists of
(a) Hinged Door

(b) Gate Door

(c) Plunger Door

FIGURE 5.3 DOOR CONSIDERATIONS
sliding plates held in tension using surgical tubing. The spring closing force is a function of the size and number of elastic tubings. The doors are cocked by attaching a tension line to one door, around the pulley, and back through the opening to the trigger release mechanism. Once released, the doors pull the line in through the opening and out of the path of the closing door. Once sealed and pressurized, the surgical tubing is removed from the chamber for easier handling.

The advantage of this design is that it triggers the doors through their own openings, avoiding shell penetration. Again, however, the threaded heads are a problem for large diameter openings. The circumferential seal is not desired, and the sliding door arrangement does not allow enough room for the fish to pass through.

The shear ring head of Design 4 (also shown in Figure 5.4) is one way of avoiding threads. However, the undesired circumferential seal is still necessary in this design.

Further design refinements are illustrated in Design 5 (Figure 5.5). Design 5 consists of an eight-inch nominal pipe with internal flanged heads. The internal flanges are designed in accordance with the "Rules for Bolted Flanged Heads" contained in the A.S.M.E. Boiler and Pressure Vessel Code. A summary of the pertinent A.S.M.E. design rules for bolted flanges is presented in Appendix C.

The internal flange design has the sealing reliability of a face seal and at the same time cuts the weight down (over an external
Figure 5.4 Design Development

a) Tripping Device

Bands

b) Shear Ring
flange) by 500%. The external nominal eight-inch flange weighs 112 pounds each. Most of the weight is concentrated in the outer diameter of 16½ inches. The sealing diameter is eight inches, requiring a thicker flange wall. The internal flange design uses 3½ inch nominal flanges which weigh only 20 pounds each. The bolts in this design must be welded from the inside because they protrude into the pressure chamber. The effective sealing diameter on the internal flange is decreased, allowing a smaller flange wall thickness.

The quick actuating doors are made up of stainless steel spheres, pulled shut through their openings by pull rods. These rods are supported from the heads in a tripod mount. Surgical tubing provides the closing force required for the initial seal. The spherical door design helps to insure a proper seal without critical alignment.

Continued refinements resulted in the selection of the final design configuration, Design 6. Design 6 is similar to Design 5 except for modifications in the sphere doors and cylinder heads. The selection of Design 6, with welded flat heads and a screwed-type access plug, is based on further weight reduction, ease in manufacture, and operating reliability. Design 6 is presented in Section 5.6.

5.5 Design Philosophy

The structural design objective of the experimental capture chamber was to provide a simple, reliable, and inexpensive means for obtaining deep water specimens. This objective included a limited operational service life, but at the same time it maintained a high
design factor of safety.

For this reason, material selection was based on short-term exposure to the ocean environment. Steels with good machinability and weldability were chosen over harder corrosion-resistant materials.

Functional support systems for the experimental capture chamber were also designed for limited service life. Emphasis was placed on reliability and simplicity.

The philosophy was to use the experimental chamber to obtain data necessary for the design of the prototype capture system. Many unknowns in the design of the experimental unit could only be solved by actual field testing.

5.6 Development of the Basic Design Configuration

Plate I shows a scaled cutaway of the experimental capture chamber. The chamber cross-section was established early in the development stages. The design evolved from the internal diameter requirements. The internal diameter had to be large enough to accommodate the sphere doors and at the same time allow accessibility to the inside. The water volume and space necessary for the specimens was also a factor in determining the internal diameter.

Spotte[61] suggests the rate of oxygen removal in a closed aquarium system is given by:

\[
O CF = \sum_{j=1}^{q} (B_j^{0.544} \times 10^{-2})
\] (1)
Where, \[ OCF = \frac{\text{mg}O_2}{\text{MIN}} \]

\( J \) = fish index  
\( q \) = number of fish captured  
\( B \) = body weight of the individual fish

Typical midwater specimens weigh on the order of two grams. One fish then would theoretically remove oxygen from the water at a rate of \( 1.45 \times 10^{-2} \text{mg}O_2/\text{minute} \). From Oceanic Observations of the Pacific (62), readings taken at 34°09'N, 121°09'W, and a depth of 400 meters, recorded a water \( O_2 \) content of 0.62 ml/l. Depending on the number of specimens trapped, Figure 5.6 shows values for the predicted life expectancy of an uncirculated 8.27 liter chamber. It should be noted that these values are conservative and are used only as guidelines. Midwater fish are adapted to living in an ocean environment of low oxygen content (the \( O_2 \) minimum occurs between 100 to 1500 meters).

The chamber is designed as a pressure vessel in accordance with A.S.M.E. Pressure Vessel Code (Reviewed in Appendix B). The basic dimensions and chamber details are shown in Plates I through III.

The design pressure was chosen to be 1000 pounds per square inch. Previous trawls taken aboard the R. V. Nautilus research vessel, (Appendix D) were towed at depths of 1200 feet. This depth produced specimens of both mesopelagic and bathypelagic fauna. The capture chamber is capable of functioning to depths of 2250 feet.

5.6.1 **Cylinder Wall Thickness**

Mild steel (ASTM grade A36), with a tensile strength of 70,000 psi, and a yield point of 52,000 psi, was chosen for the
FIGURE 5.6 PREDICTED LIFE EXPECTANCY FOR UNCIRCULATED 2 GALLON CHAMBER
experimental chamber. Using this material, the maximum stress allowed in the design was 15,000 psi.

According to the A.S.M.E. Code, the wall thickness required, due to circumferential stress:

\[ t_r = \frac{PR}{SE - 0.6P} \]  \hspace{1cm} (2)

Where,
- \( t_r \) = required shell wall thickness
- \( R \) = inner radius
- \( P \) = pressure
- \( S \) = maximum allowable stress
- \( E \) = joint efficiency (1 for seamless pipes)
- \( t_r(\text{circumferential}) = 0.265 \text{ inches minimum} \)

The required wall thickness due to longitudinal stress is given as:

\[ t_r = \frac{PR}{2SE + 0.4P} \]  \hspace{1cm} (3)

\[ t_r(\text{longitudinal}) = 0.13 \text{ inches minimum} \)

For flat unstayed heads welded to the vessel shell:

\[ t_{\text{shell}} > 1.25 \cdot t_r \]

\[ t_{\text{shell}} > 0.33 \text{ inches minimum} \]

For an 8-inch nominal schedule 80 pipe:

\[ t_{\text{actual}} = 0.5 \text{ inches} \]

5.6.2 Head Thickness

The minimum thickness required for an unstayed flat head is given by:
Where, \( t_r \) = required head thickness
\( d \) = inner diameter
\( P \) = pressure
\( S \) = maximum allowable stress
\( C = 0.5 \) for welded heads

\[
t_r = d \sqrt{CP/S}
\]

Since the openings through the heads are greater than one-half the diameter, the head thickness is designed as a bolted flange (see Appendix C).

\( t_{head} = 2.0 \) inches

The rear access plug is designed as a threaded connection as per Table UG-43, Appendix B.

5.6.3 View Port Design

The view ports are designed from a photographic standpoint. The ports are positioned 120° apart so that one can view or photograph through one side and allow light to enter the other. The 1.5 inch diameter port allows a 28 millimeter lens (on a 35 millimeter format) to be used with a focal distance of 2.5 inches to 9.5 inches.

Pressure tests to destruction were conducted on flat acrylic windows of different thickness-to-diameter ratios by the Naval Civil Engineering Laboratory, Port Hueneme, California. Their findings, plotted on Figure 5.7, show critical pressures on windows with thickness to effective diameter ratios less than 1.0.
FIGURE 5.7. RELATIONSHIP BETWEEN CRITICAL PRESSURE AND $t/D_i$ RATIO OF 1.50-INCH ($D_i$) FLAT ACRYLIC WINDOWS (From Ref. 63)
For the view port,

\[ D_1 = 1.5 \text{ inches} \]
\[ D_0 = 2.25 \text{ inches} \]
\[ D_0/D_1 = 1.5 \text{ inches} \]

From Figure 5.7,

\[ t/D_1 = 0.2 \text{ for a critical pressure of 1000 psi} \]

Therefore, the critical thickness becomes:

\[ t_{\text{critical}} = 0.3 \text{ inches} \]
\[ t_{\text{actual}} = 2.5 \text{ inches}, \text{ which allows for a factor of safety of 8} \]

Findings from the Naval Civil Engineering Lab tests on flat acrylic windows concluded that:

"...(1) Varying the \( D_0/D_1 \) ratio from 1.33 to 2.67,
(2) changing the radial clearance between the window and the flange from 0.0001 inches to 0.025 inches,
and (3) substituting a radial O-ring seal for a grease seal have no significant influence on the critical pressures of flat acrylic windows with a 0.5t/D_1 ratio."

The window shells are designed to the A.S.M.E. Code standards as communicating chambers with flat heads (Appendix B).

5.6.4 Door Closures

Spherical doors are selected to be used in the final design. For design purposes, the door closures are treated as flat plates. For an opening of 3.5 inches, the minimum door thickness is calculated to be 0.495 inches. Iteration of door size with vessel inside diameter
allows for a two-inch fish clearance path.

All O-ring seals are made of ethylene-propylene for salt water service. The seal glands are designed in accordance with the Parker O-Ring Design Handbook.(64)

5.7 Functional Systems Design

The primary functional systems include pressure chamber, pressure compensator, tripping mechanism, and door closing control system.

5.7.1 Pressure Chamber

The main purpose of the pressure chamber is to hold the hydrostatic pressure. Once the doors have been activated and sealed, the internal pressure forces increase as the chamber is raised. However, if for some reason the chamber is lowered after activation, the pressure loading would become external, causing damage to the view ports and seals. To prevent this, a one-way valve has been designed into the chamber wall so that water is allowed to enter but not exit. A safety valve has also been mounted on the chamber to prevent excessive internal loading due to pressure. If for some reason the chamber system was dropped below its design depth of 2250 feet, the safety valve would allow recovery without danger of explosion.

The internal arrangement of the chamber consists of the two closure doors and net. The net is held in position using a retainer spring. The retainer and net assembly can be removed for maintenance
requirements (refer to Plate I).

5.7.2 **Pressure Compensator**

The purpose of the pressure compensator system is to protect the specimens from embolism by compensating for chamber hydrostatic pressure drop due to volume expansion and O-ring seal compression. Since seawater is highly incompressible, small volume changes would cause catastrophic pressure drops, killing the specimens.

The theory of the pressure compensator system is to provide a reservoir of air, the compression of which serves to cushion pressure changes. Figure 5.8 shows the compensator concept. A cylinder with piston stops is precharged to a pressure equal to one-half the expected hydrostatic capture pressure. As the chamber is lowered, sea pressure acts on the piston and moves it, until equilibrium is achieved between the gas pressure and hydrostatic pressure. When the chamber is sealed and raised, the piston acts to compensate for internal pressure losses.

If the pressure drop is not cushioned, the specimen's blood, saturated with gasses at its environmental depth, would be unable to hold its dissolved gasses in solution. The result would be an embolism (the blood would literally boil).

Working on the problem of embolism in divers, J. S. Haldane, in 1907, discovered that blood could hold gas in solution until its partial pressure was equal to two times ambient pressure. For moderate depths, (to several thousand feet) seawater may be considered incompressible, gaining one atmospheric pressure per every 33 feet (65) or:
FIGURE 5.8 PRESSURE COMPENSATOR
\[ P = P_{\text{atm}} + \rho g h \]  

Where, \( P \) and \( P_{\text{atm}} \) are in pounds per square inch  
\( h \) is in feet of water

Assuming Haldane's theory holds for fish, blood saturated at a pressure of 1000 psia (depth of 2214 feet) could tolerate a theoretical pressure drop to 500 psia before embolism would occur. This is not saying that the blood of fish will act the same as human blood. Rather, it is possible that fish may also have certain tolerances to depressurization. Scientists from Marineland of the Pacific have shown that this is indeed the case. They have been successful in bringing rock-cod, caught by line fishing, directly up to 300 feet from a 900 foot depth. Divers are then able to dive down to the fish and "bleed-off" the specimen's excess gas with a hypodermic needle.

The compensator's purpose then is to maintain an internal chamber pressure well above one-half the capture depth pressure. The maximum chamber volume expansion due to pressure difference occurs at its maximum operating pressure of 1000 psi. Volume expansion by stress analysis is calculated on the end plates and chamber walls separately. Considering these and circumferential and longitudinal stresses independently, results in a conservatively high value for the volume change (worst possible case).

The chamber front and rear heads are treated as circular flat plates with supported edges (refer to Figure 5.9).
The deflection at radial distance \( r \) is given as:

\[
W(r) = \frac{q(a^2-r^2)}{64D} \left(\frac{5 + \nu}{1 + \nu} \right) \left( a^2-r^2 \right)
\]  
(Ref. 66)  \( (6) \)

and, \( W_{\text{max}} = \frac{(5 + \nu)qa^4}{64(1 + \nu)D} \)  \( (7) \)

Where:  
- \( q \) = intensity of continuous load  
- \( a \) = radius  
- \( r \) = radial distance  
- \( \nu \) = Poisson's ratio

and \( D \) is defined as:

\[
D = \frac{E t^3}{12 (1 - \nu^2)}
\]  
\( (8) \)

\( E \) = modulus of elasticity  
\( t \) = thickness of the head

The volume increase due to each head deflection becomes:

\[
V_1 = 2 \int_0^a W(r) 2\pi r \, dr
\]  
\( (9) \)
Substituting equation (6) for $W(r)$:

$$V_1 = \frac{4 \pi a}{64D} \int_0^a \left( a^2 - r^2 \right) \left( \frac{5+\nu}{1+\nu} \frac{a^2 - r^2}{a^2 - r^2} \right)$$

(10)

The deflection in the chamber walls due to circumferential stress considerations (refer to Figure 5.10) is given as:

$$W(x) = \frac{P \lambda^4}{64D\alpha^4} \left(1 - \frac{2 \sin \alpha \sinh \alpha}{\cos 2\alpha + \cosh 2\alpha} \sin \beta x \sinh \beta x \right.$$

$$- \frac{2 \cos \alpha \cosh \alpha}{\cos 2\alpha + \cosh 2\alpha} \cos \beta x \cosh \beta x \right) \text{ (Ref. 66) (11)}$$

The maximum deflection occurs at $x = 0$,

$$W(x=0) = \frac{P \lambda^4}{64D\alpha^4} \left(1 - \frac{2 \cos \alpha \cosh \alpha}{\cos 2\alpha + \cosh 2\alpha} \right)$$

(12)

Where:

- $P$ = pressure (psi)
- $\lambda$ = length
- $D$ = defined in equation (8)
- $t$ = thickness of shell
- $E$ = modulus of elasticity
- $v$ = Poisson's ratio
- $\alpha = \frac{\beta \lambda}{2}$

$$\beta^4 = \frac{E t}{4a^2 D} = \frac{3(1-v^2)}{a^2 t^2}$$
FIGURE 5.10 CYLINDER SHELL DEFLECTION
The volume increase from chamber wall expansion due to circumferential stresses becomes:

\[ V_2 = 2 \int_0^{L/2} W(x) \cdot 2\pi r \, dx \]  

(13)

Where \( W(x) \) is defined by equation (11).

The change in volume due to longitudinal stresses (Figure 5.11) is given as:

\[ V_3 = \pi R_1^2 \Delta l \]  

(14)

\[ \Delta l = \frac{qL}{E(A)} \]  

(15)

Where \( q = \text{load} = \pi R_1^2 P \)

\( P = \text{internal pressure} \)

\( R = \text{radius} \)

\( A = \pi (R_2^2 - R_1^2) \)

![FIGURE 5.11 LONGITUDINAL DEFLECTION](image)

The total chamber volume change due to wall stresses becomes:

\[ \Delta V = 2V_1 + V_2 + V_3 \]
For the experimental capture chamber,
\[ \Delta V = 0.185 \text{ in}^3 \text{ max.} \]

From the Parker O-Ring Handbook\(^{64}\) a 1000 psi pressure pressing against the 4.06 inch diameter O-rings with a compression force of 1,015 lbf/linear inch, causes a 50 percent O-ring compression. The volume change due to compression of the door seals becomes:
\[ \Delta V \text{ seals} = 0.44 \text{ in}^3 \]

The change in volume due to thermal expansion from 33°F to 72°F (using \(6.5 \times 10^{-6} \text{ in}/\text{in}/\text{°F}\) becomes \(0.15 \text{ in}^3\). The total maximum volume change of chamber and seals becomes,
\[ \Delta V = 0.775 \text{ in}^3 \]

The internal volume of the pressure compensator must be large enough to compensate for the .775 cubic inch volume change by maintaining the pressure well above the theoretical range of 500 psi.

The design criteria for the pressure compensator has been set to maintain the chamber pressure to at least 90 percent of the original capture pressure. Referring to Figure 5.8:
\[ P_1 V_1 \geq P_2 V_2 \quad (16) \]

Where,  
- \(P_1\) = capture pressure  
- \(V_1\) = one-half compensator volume (when compensator is precharged to one-half \(P_1\))  
- \(P_2\) = pressure to be maintained by the compensator  
- \(V_2 = V_1 + \Delta V\)

therefore,  
\[ P_1 V_1 \geq 0.9 P_1 (V_1 + \Delta V) \]
\[ V_1 \geq 9 \Delta V \]
Therefore, the compensator volume:

\[ V_{\text{comp}} \geq 18 \Delta V \]

The compensator designed for the experimental capture chamber has a volume of:

\[ V_{\text{comp}} = 102 \text{ in}^3, \text{ or } (132)\Delta V. \]

In normal operation without the use of the pressure compensator, the chamber pressure would drop \(3 \times 10^3\) psi for a one percent \(\Delta V\). Thus, the experimental chamber would drop from 1000 psi to 600 psi without the compensator. The compensator maintains the pressure to within 900 psi.

The compensator designed for use on the experimental chamber is shown in Plate IV. For simplicity, a "pop valve" is used instead of a piston. The "pop valve" holds the pressure on the precharge gas side. However, once the chamber and compensator reach a depth beyond which the hydrostatic sea pressure and precharge pressure are in equilibrium, the "pop valve" is displaced, allowing water to move in or out of the compensator. In this design, gas separation from the chamber is neglected.

5.7.3 The Tripping Mechanism

The different alternatives available for tripping the chamber doors shut at depth are reviewed in Section 3.4. The simplest and most inexpensive method is to use the depth/time trip. Three different designs are considered for tripping the experimental capture chamber.
For long trawls, the tripping mechanism designed in Figure 5.12 may be used. It utilizes a magnesium release encased in a two-halved Plexiglas housing. Initially, the tension is adjusted so that a seal is made between the two housing halves; $P_1$ remains at one atmosphere while $P_2$ is increased, causing the seal to become tighter. When the hydrostatic pressure equals the burst disk rupture pressure, water enters the housing to the magnesium release. When the release parts, so do the housing halves. The tension is then broken, tripping the doors. If magnesium is used in any tripping device, it is important to design it outside the fish chamber. Magnesium becomes a toxin to the specimens.

For shorter trawl times, a "lifesaver" trip may be substituted for the magnesium release. Here again the burst disk ruptures at depth causing the water to enter and dissolve the candy lifesavers.

A hydraulic release is shown in Figure 5.13. The burst disk ruptures at depth causing water to enter the lines to the hydraulic piston. Time is controlled by an orifice or capillary in the line. The hydraulic piston rotates the cam, causing the swing-arm to trigger.

5.7.4 Door Closing Control System

The calculated compression force required to seal each door shut is listed in Table 2.
FIGURE 5.13 HYDRAULIC RELEASE


**TABLE 2**

<table>
<thead>
<tr>
<th>% Compression</th>
<th>Force Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>62.8 lbf</td>
</tr>
<tr>
<td>10</td>
<td>163.8 lbf</td>
</tr>
<tr>
<td>20</td>
<td>376.8 lbf</td>
</tr>
</tbody>
</table>

From this requirement, two different closing systems are designed; one mechanical and one hydraulic.

The mechanical system is shown in Plate V. Sealing force is provided by six bands of surgical tubing on each door. The bands are designed so that they can be loaded two at a time. Together the bands provide 80 pounds of force, which is considered marginal. Because of the flow of water through the chamber, the rear door must close before the front door can seal. Tripping the doors together becomes a problem in that they must be connected to each other by control wires.

A more applicable system to the simultaneous triggering arrangement is the hydraulic control system shown in Plates VI and VII. In this system, double actuating hydraulic cylinders are open to sea pressure on one side. The other side is connected by pressure lines to a gas reservoir. Initially, the hydraulic fluid and pressure is constrained in the receiver side of the piston by a rupture disk in the pressure line. When the chamber is lowered to the desired depth, the rupture disk bursts, allowing the hydrostatic sea pressure to actuate the piston, ramming the doors shut.

In this system, both doors may be actuated by a single rupture disk. Activation depth may be varied by using different
thicknesses of replaceable disks.

Each cylinder has a bore of 1.125 inches and a stroke of 3.5 inches (although only a two-inch stroke is required). The system is designed to produce a sealing force on each door of at least 400 pounds at a minimum depth of 1000 feet. The maximum sealing force is controlled by the volume of the pneumatic reservoir. The maximum amount of hydraulic fluid displaced by the two cylinders into the reservoir is seven cubic inches. Given a hydrostatic force of 500 psi on the closing side of the piston, (piston area = 1 in²) the maximum allowable pressure in the reservoir opposing it must be 100 psi, so:

\[ P_1 V_1 = P_2 V_2 \]
\[ 14.7 V_1 = 100 V_2 \]
Where \( V_2 = V_1 - 7 \text{ in}^3 \)
\[ 14.7 V_1 = 100(V_1 - 7) \]
Therefore, the initial reservoir volume,
\[ V_1 \geq 8.2 \text{ in}^3 \]

5.8 Environmental Control

Pressure and temperature are the two key environmental problems encountered when retrieving deep sea specimens. Pressure is maintained by a pressure compensator (Section 5.7.2).

The steel chamber provides small resistance to heat transfer. However, since the specimens are contained within a pressurized environment, the net trawl can be hauled up onto the boat as fast as possible. Once on board, the chamber is placed into a temperature
controlled ice bath.

5.9 Hydrodynamics

Towing the experimental capture chamber behind the Isaacs-Kidd Midwater Trawl requires that the chamber provide its own dynamic lift. A wind tunnel model of a lifting vane was tested under dynamic similitude for a vehicle being towed at two knots through the water. It was found that the wing surface area, necessary to keep the chamber planing horizontal, would require a ten-feet wingspan. This would require making a tow sled for the chamber in order to support the wings.

Because of the forgoing, it was decided not to drag the capture unit behind the trawl, but rather, to attach the cable and pull the chamber through its own center of gravity. In this configuration, the capture net is rigidly attached to the front of the chamber. The extra moment caused by the forward net must then be counteracted with a restoring moment. To do this, a plankton tow net is attached to the rear door strut and dragged behind the chamber. Dive planes are mounted directly under the center of pull of the towing cable. The downward force on the dive planes in combination with the upward pull of the cable keeps the unit planing horizontal at its proper tow depth. Figure 5.14 shows the final design in its towing configuration.
5.10 **Specifications**

Table 3 lists a summary of the capture system specification data.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Chamber</strong></td>
<td></td>
</tr>
<tr>
<td>a. max. rated pressure</td>
<td>1000 psi @ 2247 feet sea water</td>
</tr>
<tr>
<td>b. normal operating pressure</td>
<td>500 psi @ 1123 feet sea water</td>
</tr>
<tr>
<td>c. bursting pressure</td>
<td>5780 psi (safety valve protection)</td>
</tr>
<tr>
<td>d. diameter</td>
<td>8&quot; nominal</td>
</tr>
<tr>
<td>e. length</td>
<td>17.5 inches</td>
</tr>
<tr>
<td>f. weight (dry)</td>
<td>130 pounds empty</td>
</tr>
<tr>
<td>g. weight (in water)</td>
<td>150 pounds full</td>
</tr>
<tr>
<td>h. internal volume</td>
<td>112 pounds</td>
</tr>
<tr>
<td><strong>2. Pressure Compensator</strong></td>
<td></td>
</tr>
<tr>
<td>a. max. rated pressure</td>
<td>6000 psi</td>
</tr>
<tr>
<td>b. normal operating pressure</td>
<td>500 psi</td>
</tr>
<tr>
<td>c. diameter</td>
<td>3.5 inches O.D.</td>
</tr>
<tr>
<td>d. length</td>
<td>14.5 inches</td>
</tr>
<tr>
<td>e. internal volume</td>
<td>102 cubic inches</td>
</tr>
<tr>
<td>f. weight (dry)</td>
<td>16 pounds</td>
</tr>
<tr>
<td>g. weight (in water)</td>
<td>13.8 pounds</td>
</tr>
<tr>
<td><strong>3. Hydraulic Closure Control System</strong></td>
<td></td>
</tr>
<tr>
<td>a. max. rated pressure</td>
<td>1500 psi</td>
</tr>
<tr>
<td>b. hydraulic cylinder</td>
<td></td>
</tr>
<tr>
<td>bore</td>
<td>1.125 inches</td>
</tr>
<tr>
<td>stroke</td>
<td>3.5 inches</td>
</tr>
<tr>
<td>weight</td>
<td>2 pounds each</td>
</tr>
<tr>
<td>c. activation depth</td>
<td>adjustable 400-2000 feet</td>
</tr>
</tbody>
</table>
6. **Construction of the Experimental Capture Chamber**

6.1 **Introduction**

With the exception of critical pressure welding and heat treating, the experimental capture chamber was manufactured entirely in the engineering machine shop at California State University, Northridge. The facilities available, along with the machining procedures were discussed in advance so that the final design would be compatible with machine shop practices.

6.2 **Materials and Machining**

The flat end plates, end plug, window shells, and cylinder walls were all constructed of low strength steel. Steels have been used successfully in the ocean for hull structures, tanks, fairings, buoys, and cables.\(^{(65)}\) Low strength steels (those having a yield strength less than 50,000 to 60,000 psi) were chosen over high strength steels because they can be easily formed, machined, and joined. They resist fatigue and are not subject to brittle-type fractures. Repairs on low strength steels can be made with little difficulty.

With high strength steels, however, extreme care must be taken to avoid stress concentrations and defects. High stresses and defects may cause brittle-type fractures well below the yield strength of the material.

Non-stainless steel corrodes at a rate of 0.005 inches per year in sea water.\(^{(65)}\) However, pit growth may be as high as 0.05 inches per year. For short-term exposure to saltwater, it was felt
that this much corrosion could be tolerated. A protective coating was applied to help resist corrosion (see Section 6.4).

Stainless steels have been found to resist corrosion as long as the oxide film remains on the surface of the metal. However, in a low oxygen environment, (the chamber operational depth is well within the oxygen minimum of the ocean)\(^67\) the protective film tends to break down. In static sea water, (after the chamber doors have closed) all stainless steels are susceptible to crevice corrosion and pitting.

For these reasons, along with a cost trade-off analysis, low-strength, non-stainless steel was chosen for the experimental capture chamber. All pressure parts were constructed from 1020 and 1022 hot-rolled steel bars and machined to their initial dimensions (hot-rolled steel is more normalized stresswise than cold-rolled steel).

The chamber unit was then taken to an A.S.M.E. certified pressure vessel welder where the end plates, and window ports were welded. Afterwards, the unit was normalized by heat-treating to relieve stress concentrations. Figure 6.1 shows the welded vessel after heat-treating.

Due to heat distortion of the plug threads and conical window ports, all final machining was performed after completion of the welding and heat-treating processes. For this reason, the chamber leg supports were made to detach so that the chamber unit could be re-chucked into the lathe.

The viewing ports were machined from 2½ inch thick optically
clear Plexiglas. Silicone rubber helped to form a positive seal between the window plugs and port frames. Figure 6.2 shows the completed chamber and support system components.

6.3 Special Considerations

In this description many of the minor details have been omitted. However, some important considerations are vital for successful operation. It is important that O-rings be made from the correct material for their application. For example, O-rings made for hydraulic fluids (nitrile) should not be exposed to saltwater. Saltwater O-rings (ethylene-propylene) should not be exposed to hydraulic fluids. In some cases this becomes a problem; as when sealing sea water and hydraulic fluid at the same time. For short applications, as in the case of the experimental capture unit, the use of distilled water in the hydraulic systems instead of hydraulic fluid helps to solve this problem.

Many of the commercial fittings (check valves, hand valves, and relief valves) are not manufactured for saltwater application. In all such instances the fittings had to be completely overhauled by replacing the seals with ethylene-propylene O-rings.

Special consideration must also be given to pressure gages and hydraulic cylinders. In both cases the equipment has been designed for internal pressure; not for external/internal pressure cycles.

The pressure gage used is a Hydro-Pak Gauge, manufactured by
CPW Valve and Instrument Ltd., Canada. It contains a combination plastic case and O-ring sealed lens, which is excellent for saltwater applications. However, to protect the gage and casing from the enormous hydrostatic pressure found at the experimental capture unit's operating depth, modifications were necessary. The case was drilled and then fitted with a small rubber bladder. The case and bladder were filled with mineral oil. Underwater, the bladder, "sensing" the external pressure from the sea, collapses, forcing more oil into the gage housing. This action maintains a zero pressure gradient across the plastic housing.

Hydraulic cylinders are designed for internal pressures. On some cylinders, the end plugs form their seal by being forced against a machined lip on the cylinder wall. Shear lock-rings were necessary to restrain the plugs from collapsing under external pressure.

The primary door O-rings were seated in machined dovetail grooves. However, as an extra precaution to keep them from being forced out of their grooves while under tow, they were bonded to the groove seat with neoprene cement.

6.4 Protective Coatings

Protection of marine surfaces through the use of coatings consists of covering them with materials that are more resistant to saltwater corrosion than the surface itself. There are a number of coatings on the market, but special attention must be given to coatings that come in contact with live marine specimens. Many
coatings contain an "anti-fouling" formula; all of which are toxic to the marine organisms. Metallic coatings, such as zinc and cadmium, used for cathodic protection, are all toxic to marine life.

Epoxy was chosen for use in coating the experimental chamber. Epoxy has been found to give good protection to steel for three years at shallow depths. At 6,800 feet, an unscribed panel showed no deterioration after three years. A scribed panel had medium-sized blisters after the same period. (65)

6.5 Testing

Initial calibration tests for the depth triggering mechanism, were conducted on burst disks manufactured from varying materials and thicknesses. Figure 6.3 is a calibration scale showing the proper burst disk selection for the desired depth range. Activation depth of the triggering mechanism can be adjusted by simply varying the rupture disks.

The following systems were lab-tested under simulated conditions:

(a) The pressure compensator was charged to 1000 psi for 24 hours. Initial results showed leakage through the flat gasket in the compensator head assembly. The flat gasket was replaced with double O-ring seals. Subsequent tests proved successful.

(b) The pressure relief valve for the capture chamber was tested and calibrated to relieve at 1350 psi.
<table>
<thead>
<tr>
<th>Test Pressure (psig)</th>
<th>Depth Range (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>700</td>
</tr>
<tr>
<td>400</td>
<td>800</td>
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<td>900</td>
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<td>700</td>
<td>1000</td>
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<tr>
<td></td>
<td>1100</td>
</tr>
<tr>
<td>800</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>0.001&quot; Aluminum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.002&quot; Aluminum</td>
</tr>
<tr>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>1600</td>
</tr>
<tr>
<td>600</td>
<td>1700</td>
</tr>
<tr>
<td></td>
<td>1800</td>
</tr>
<tr>
<td>0.001&quot; Brass</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 6.3**  BURST DISC CALIBRATION
(c) The pressure compensator "pop valve" was charged on one side to 750 psi. The other side was then gradually charged with pressure until the "pop valve" was activated. Activation occurred at exactly the calibrated pressure (750 psi).

(d) The hydraulic closing system and depth activator were successfully triggered at an equivalent depth of 1000 feet using a 0.002 inch aluminum burst disk.

(e) The capture chamber was immersed in a tank and filled with water. The doors were activated and sealed while submerged. The chamber was then removed from the water tank and pneumatic pressure was pumped into the pressure compensator. The chamber was then pressurized through the compensator to 1000 psi. No leaks were observed.

6.6 Reliability

A "healthier" and more reliable environment is achieved by minimizing the amount of metal in direct contact with the sea water. Care has been taken to coat the metal surfaces with epoxy. However, in rubbing parts and sealing surfaces, metal is necessarily exposed. Commercial valves and other parts often contain copper or its alloys, which are extremely toxic to the specimens. Plastic and rubber products however, are non-toxic when aged for a period of a few days in sea water.
7. **Operating Procedures and Results**

The experimental unit can be completely dismantled and reassembled for maintenance and repair purposes.

7.1 **Preparation**

The front door closure and net assemblies must first be bolted onto the front head of the pressure vessel. The forward door O-ring is then lubricated and the forward spherical door attached from inside the chamber (through the rear access port). The inside net is then fastened to the net retainer ring located inside the chamber.

After lubricating the O-rings on the rear door seals, the rear door assembly is threaded into the access port.

The hydraulic lines leading to and from the hydraulic cylinders must be bled of all entrapped air bubbles. This is accomplished on the receiver lines, located between the depth-triggering mechanism and the hydraulic cylinders, by disconnecting the lines at each cylinder and pumping distilled water through the top opening of the depth-triggering mechanism (refer to Plate VII). The proper burst disk for the desired activation depth is then selected from Figure 6.3 and inserted into the depth-triggering mechanism. It is important that the burst disk be inserted below the distilled water level. The pneumatic atmospheric pressure line is then connected from the triggering mechanism to the hydraulic reservoir. The depth triggering system is now ready for operation.

The sea water intake lines are bled by disconnecting them at
each of the hydraulic cylinders and pumping distilled water through the sea water inlet valve (one-way valve). Tightening all pressure fittings and checking for leaks completes the pre-trawl preparation on the depth-triggering and door-actuating systems.

The pressure compensator is then precharged with air pressure to approximately one-half the normal operating depth pressure. The "pop valve", located in the pressure compensator head, must be fully engaged before the initial charge.

The stabilizer and dive planes are attached to the chamber support legs. After attaching the rigging and sea anchor to their supports, the entire capture unit is ready for operation. Figure 7.1 shows the entire capture unit.

At the completion of the trawling operation, the forward and rear door actuating assemblies, along with the dive planes and stabilizers, can be removed without disturbing the internal chamber pressure. In this manner, the chamber can be easily transported to the laboratory as a pressurized aquarium.

If it becomes necessary to make more than one trawl on the same day, the capture unit can be easily reset. The door and triggering systems are prepared by opening the door-reset-valve and pumping distilled water back through the top of the depth-triggering mechanism. The "pop valve" is then replaced and the pressure compensator recharged.
7.2 **Operation**

On May 2, 1974, the experimental capture system was tested in the San Pedro Channel aboard the research vessel *R. V. Nautilus* (Appendix D). The weather conditions were: high overcast with a prevailing three-foot southwest swell. The equipment necessary for the operation included the capture unit, plankton tow nets (to be used as sea anchors), and deck winch.

At 9:30 a.m., the hydrodynamic tow characteristics of the capture system were tested by towing the unit at two knots, at a depth of three feet. One plankton net was trailed behind the capture unit to help its stabilization in the water.

It was found that one plankton net was not enough to keep the capture unit headed in the proper direction. As a result, the chamber yawed 60° to one side. However, it was noted that the unit was stable in pitch and roll, and continued to maintain a horizontal attitude through the water.

The unit was brought aboard the vessel and rigged with a second plankton net in series with the first. The combination of the two nets provided enough drag (and restoring moment) to successfully keep the capture unit stable about all axes. Figure 7.2 shows the chamber in its towed configuration.

The initial deep sea trial was conducted with the chamber set to actuate at a depth of 1000 feet. A 0.002-inch aluminum rupture disk was inserted into the tripping mechanism. The pressure compensator was precharged to 250 psi. The unit was then lowered over the stern of the
vessel by the deck winch. Vessel trawl speed was two knots. The total depth below the boat to the ocean bottom was recorded to be 2350 feet.

As the chamber descended, sea pressure acted against the "pop valve" until the sea pressure achieved equilibrium with the air pressure inside the pressure compensator. At a depth of 560 feet, the "pop valve" actuated, allowing the sea water to enter the pressure compensator and compress the gas inside. At a depth of approximately 1000 feet, the burst disk ruptured in the triggering mechanism, slamming the front and rear doors shut. Total time to depth was ten minutes. The trawl depth was estimated from the length of cable released and the angle in which the cable entered the water.

The recovery operation began fifteen minutes after the capture unit achieved its maximum depth. As the unit began its ascent to the surface, the pressure gradient increased across the chamber walls. Pressure loss, due to expansion of the chamber walls, was compensated for by the gas pressure inside the pressure compensator expanding against the entrapped volume of water inside the chamber. The recovery operation lasted 30 minutes.

7.3 Results

The entire capture system was recovered in good condition. Both doors successfully sealed against their O-ring seats. The pressure gage indicated that the water pressure inside the chamber was 550 psi. There was no damage to the plastic gage housing. Small free-swimming
organisms, identified as comb jellyfish, and other planktonic specimens, could be viewed through the window ports. Figure 7.3 shows the organisms as viewed through the ports.

No fish specimens were captured on this trawl. However, the plankton tow nets, which trailed behind the capture chamber, contained many more organisms, including a lantern fish. This would indicate that the doors in the pressure chamber closed before more organisms had a chance to be funneled through the capture unit's own net. (The capture unit's net is twice the diameter of either of the plankton nets.)

More specimens could be captured in the chamber by simply towing the unit above its activation depth for about 20 minutes before dropping it down lower to activation.

In this trial run, the pressure compensator was able to maintain the pressure inside the chamber from 597 psi, found at 1342 feet, to 550 psi -- a drop of only 47 psi. The equivalent depth maintained inside the chamber therefore was 1,236 feet.
8. Recommendations and Conclusions

8.1 Future Recommendations

While much has been learned about the retrieval possibilities of deep-ocean specimens, there are still a number of unknowns to contend with. The capture model used here features some broad assumptions about the biological requirements of deep-ocean specimens. In this model, temperature requirements were neglected. It is suggested that an ice bath and later a refrigeration system be available to keep the water inside the capture chamber chilled to 5°C. A thermometer should be added to the chamber to monitor the temperature.

Dissolved gasses could be minimized by utilizing a rubber diaphragm or piston to separate the air pressure from the sea water in the pressure compensator.

A rubber bladder could also be used in conjunction with a reservoir to separate the hydraulic fluid from the sea water and to keep it from entering the hydraulic system. In this system, it would become unnecessary to clean out the hydraulic lines after each use, and thus eliminate the need to bleed them.

Based upon this thesis study, there is every reason to expect that current knowledge levels in design could be successfully applied to deeper capture systems, capable of depths down to 1000 meters and beyond.

It is recommended that fiberglass pressure vessels, capable of pressures up to 1500 psi, be considered from a corrosion resistance standpoint. For both deeper and longer exposure applications, high
strength 316 stainless steel could be used, if properly protected with an epoxy coating.

The use of an acoustic tripping device to remotely activate the chamber doors from aboard the vessel, would lend itself well to this design. The doors could also be made to trigger by a fish passing through and changing the inductance on coils wound around the entrance of the chamber. This method would help to remove some of the "trial and error" involved in capturing deep-sea fish. A net closing device would also help to keep shallow water specimens from entering the net during its initial descent.

The chamber unit is capable of providing experimental results on the decompression of deep sea specimens. It is suggested that further studies be made on this subject. It may be possible to collect and decompress, for laboratory display purposes, many different types of live specimens -- specimens considered rare today.

With the addition of a transfer lock, specimens may be transferred directly from the capture chamber into a pressurized aquarium. If necessary, the capture chamber itself may in fact become a self-contained pressurized aquarium (see Appendix A).

One future application of the capture chamber is to use it as an in situ water sampler. There is no existing water bottle capable of trapping a water sample at depth and transporting it at the in situ pressure to a shore laboratory for dissolved-gas analysis. (65)

The findings discussed herein imply that collecting deep-sea organisms in a capture chamber under their environmental conditions
(pressure, temperature) is feasible. The possibilities of decompression, study, and display of live specimens under pressure offer further encouragement for pushing ahead with this study.

8.2 Conclusions

One of the basic justifications for choosing to build an experimental capture system was to obtain results confirming the feasibility of such a device for scientific study. The question of whether a pressurized capture chamber is feasible has been answered in practical demonstration. In particular, it has been shown that such a device can be dropped into the ocean, triggered at depth, and recovered to the surface while maintaining the hydrostatic pressure found at its operating level.

The following, summarize principle results from this study believed to be unique in the design of a deep-sea capture system:

(a) A device can be made to trigger at operational depth and maintain most of the hydrostatic pressure inside while being recovered.

(b) Organisms caught in this device are retrieved in good condition (uncrushed and free-swimming).

(c) Such a device could be used as a decompression chamber in order to obtain results on whether deep-sea fish can be decompressed or not.

There is no doubt that deep-sea fish can be captured in the experimental unit. Although the unit's net diameter is only two feet,
lantern fish have been successfully caught in nets with one foot diameter openings. It is worth noting here that in the design and construction of this unit, it was found that even the smallest and most straightforward engineering problems become time consuming. The project represented a challenging engineering development task and learning experience involving many disciplines.

The sea does not yield her secrets easily. An oceanographic tool, such as the deep sea capture system, can be a most valuable and effective facility for use in achieving knowledge about the abyss, and the creatures that live in it.
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BIBLIOGRAPHY


APPENDIX A

Pressurized Aquarium System

An open-system pressurized aquarium is described. The unit is currently in operation at California Institute of Technology under the supervision of its designers, H. A. Lowenstam and James A. Westphal. The open-system concept described here is exceptionally adaptable to the deep-sea capture chamber. By simply adding inlet and exhaust ports to the chamber walls, the capture unit may be plugged into the pressure filter system becoming itself, a pressurized aquarium.

The suitability of the apparatus, shown in Figure A.1, for long-range pressure studies has been demonstrated by maintaining experimental animals at elevated pressures for periods of up to six months. The system thus far has been used only on invertebrates; mainly because of the difficulty in collecting unharmed fish specimens.

The aquaria in operation is a one-liter cast 316 stainless steel cylinder with external end caps containing the windows. It is capable of pressures up to 5,000 meters equivalent depth. The windows are tapered (15° total angle) "Lucite" plugs with polished faces.

The pump system produces a continuous flow of sea water at constant pressure. A pressure interchange chamber is used to prevent the sea water from coming in direct contact with the pump. A rubber bladder in the interchange chamber allows the sea water to be totally isolated from the pump and from the majority of the raw metal surfaces. Flowrate is regulated by a 0.0045-inch bore capillary tube.
FIGURE A.1 PRESSURIZED AQUARIUM SYSTEM (From Ref. 59)
The flowrate becomes a function of aquarium pressure and length of capillary.

Referring to Figure A.1, sea water fills the bladder in the interchange chamber where it is pressurized by the pumping of distilled water around the outside of the bladder. Valve (2), at the outlet of the system is open, and valve (1) in the distilled water branch is closed. Under these conditions, sea water flows through the aquarium from the interchange chamber out the capillary exhaust. At the end of the positive-displacement pumping cycle, valve (2) in the exhaust is closed; valve (1) is open. At this point, sea water from the sump (pressurized at 15 psig) refills the bladder displacing the distilled water back to its reservoir. Check valves retain the pressure in the aquarium at all times. At the end of the recharge cycle, valve (1) is closed again and the pump restarted. Finally, valve (2) is opened and flow through the aquarium is reestablished. The recharge cycle takes about three minutes.

The pump is an air-driven hydraulic constant output pressure system (manufactured by Sprague Engineering Co.). Air pressure on one piston drives another piston which pumps the distilled water. The output pressure of the pump is regulated by the input air pressure. With a piston area ratio of 100:1, one atmosphere of air applied to the pump produces an output of 100 atmospheres of distilled water.

A 0.45 "Millepore" filter disk is required to remove all particulate material from the water prior to entering the capillary section. This is particularly important when carnivorous animals are
fed live food.

If some failure in the pumping system occurs, a small valve at the sea water side of the interchange chamber keeps the rubber bladder from extruding into the pressure lines. This valve is mechanically closed by the collapsing bladder.

A "feeding loop" is installed in the aquarium inlet lines for the introduction of food. Manually operated valves allow the operator to introduce the food without loss of pressure in the aquarium.
The following rules apply to pressure vessels with design pressures greater than 15 psig but not exceeding 3000 psig.

I. Cylinder Walls

The minimum required thickness for cylinder walls subjected to pressure is given by the larger of A) or B):

A) Circumferential Stress

\[
t = \frac{PR}{SE - 0.6P}
\]

B) Longitudinal Stress

\[
t = \frac{PR}{2SE + 0.4P}
\]

Where:
- \( t \) = minimum thickness
- \( P \) = pressure
- \( S \) = allowable stress
- \( E \) = joint efficiency
- \( R \) = inner radius
II. Unstayed Flat Heads

The minimum required thickness for unstayed flat heads is given by:

\[ t = \frac{d \sqrt{cp/s}}{c} \]

Where:  
- \( p \) = pressure  
- \( s \) = maximum allowable stress  
- \( d \) = diameter  
- \( c \) = constant from Figure B.1

When flat heads become an integral part of the shell, the cylinder wall thickness must be 1.25 times the required minimum thickness.

III. Formed Heads, Pressure on Concave Side

A) Ellipsoidal Head

\[ t = \frac{pd}{2se - 0.2p} \]

- \( d \) = inside length of major axis  
- \( e \) = joint efficiency = 0.6

B) Hemispherical Head

\[ t = \frac{pr}{2se - 0.2p} \]

- \( r \) = inside spherical radius

IV. Quick Closures - Doors

Any device which meets safeguards of A), B), C), below, meet the intent of this code:
FIGURE B.1 UNSTAYED FLAT HEADS
A) Closures must be fully engaged before the pressure can build up.

B) Pressure tending to force the closure clear of the vessel must be released before the closure can be opened for access.

C) A pressure indicator device must be visible.

V. Openings

Openings should be reinforced as per VI below. Any opening greater than one-half vessel diameter must be designed as a flange. Fittings need no reinforcement.

VI. Reinforcement

The reinforcement area required for openings is given by:

\[ A = 0.5 \, d \, t \]

Where:  \( d \) = diameter of opening  
\( t \) = thickness of head

Reinforcement area can only be counted \( \leq 2\frac{1}{2} \) times the wall thickness perpendicular to and \( 2\frac{1}{2} \) times the wall thickness on the side of the shell. The material used to reinforce an opening must be of equal quality to the wall material. As an alternative to using reinforcement, \( 2C \) may be substituted into the head thickness equation in Section II above. For openings greater than one-half the diameter of the vessel, the head must be designed as a bolted flange (see Appendix C).
VII. Communicating Chambers

Threaded connections (pipes) may be screwed into threaded holes in the vessel wall provided the minimum number of threads are engaged. Table UG-43 shows the required thread engagement.

Saddles can be used to provide proper plate thickness.

<table>
<thead>
<tr>
<th>Size of Pipe</th>
<th>(\frac{3}{4})</th>
<th>1</th>
<th>1(\frac{1}{2})</th>
<th>2</th>
<th>2(\frac{1}{2})</th>
<th>3</th>
<th>4-6</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threads Engaged</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Plate Thick</td>
<td>0.43</td>
<td>0.61</td>
<td>0.70</td>
<td>1.0</td>
<td>1.25</td>
<td>1.5</td>
<td>1.62</td>
<td>1.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

VIII. Pressure Relief

Pressure relief valves must not let the pressure become 10% above the normal design working pressure. Burst disks may be used where leakage is critical. All pressure relief valves should be connected in the vapor space above any liquids.

IX. Corrosion

When corrosion rates are known, add enough material for the desired life of the vessel. Otherwise, the vessel must be inspected regularly. Special linings may be used to prevent corrosion. Paint, however, is not considered a lining.

X. Welded Head

The welded head thickness requirements are shown in Figure B.2.
FIGURE B.2 WELD DETAIL

t ≈ 3t_s
a = t_s
b = t_s
t_w = t_s
x can be 0
APPENDIX C

SUMMARY OF A.S.M.E. DESIGN RULES
FOR BOLTED FLANGES

Figure C.1 shows the symbols used for an integral-type flange.

FIGURE C.1 BOLTED FLANGE
Definitions of Figure C.1:

A = O.D. of flange
B = I.D. of flange
B₁ = B + g₀
C = bolt circle diameter
G = diameter of gasket load
g₀ = thickness of hub
g₁ = thickness of hub at back of flange
H = total hydrostatic end force = 0.785G²P
H₀ = force on area inside of flange = 0.785B²P
H₇ = gasket load = W - H
Hₚ = joint compression load = 0 for 'O'-ring
Hₜ = H - H₀
h = hub length
h₀ = distance from bolt circle to H₀
h₉ = distance from gasket load to bolt circle
h₀ = √BG₀
hₜ = distance from bolt circle to Hₜ
R = C - B - g₁

I. Bolt Loads

A) Operating Conditions

The minimum required bolt load for operating conditions (lbf) is:

\[
W_m = H + H_p = 0.785G^2P
\]

*With O-ring gasket only.
B) Total required bolt cross-sectional area:

\[ A_m = \frac{W_m}{S_b} \]

Where: \( S_b \) = allowable bolt stress at the design temperature

II. Flange Moments

A) Operating Conditions

The total flange moment:

\[ M = M_D + M_T + M_G \]

Where: 
\( M_D = H_D h_D \) (inch-pounds)
\( M_T = H_T h_T \)
\( M_G = H_g h_g \)

B) Gasket Seating

\[ M_o = \frac{W(C-G)}{2} \]

III. Flange Stresses

A) Longitudinal hub stress

\[ S_H = \frac{M_o}{Lg_1^2 B} \]

Where: 
\[ L = \frac{t_e + 1}{1.5} + \frac{t^3}{d} \]
\[
e = \frac{0.95}{h_0}
\]
and: \( d = 2.66 \)

B) Radial Stress

\[
S_R = \frac{(1.33 \ t e + 1)M_0}{L \ t^2 \ B}
\]

C) Tangential Stress

\[
S_T = \frac{3 \ M_0}{t^2 B} - 2 \ S_R
\]

IV. Allowable Flange Stresses

The maximum allowable stress, \( S \), must be satisfied by A) through D) below:

A) \( S_H < 1.5 \ S \)
B) \( S_T < S \)
C) \( \frac{S_H + S_R}{2} < S \)
D) \( \frac{S_H + S_T}{2} < S \)
APPENDIX D

The R. v. Nautilus, shown in Figure D.1, is a fifty-foot research vessel and floating laboratory operated by the Southern California Ocean Studies Consortium. The SCOSC was set up by five state colleges (including Northridge) in order to support their programs in Ocean Studies.

The Nautilus, acquired by the SCOSC in 1971, was originally built as a purse seiner and then converted to research by the California Department of Fish and Game. It has a cruising speed of nine knots and a range of 1,000 nautical miles. Deck handling equipment includes a one ton capacity boom, trawl winches (with 1500 feet of 7/16" cable and 3000 feet of 3/8" cable), and an "A" Frame.

Currently, the vessel is being used by the colleges for instructional purposes together with research and development in the fields of marine biology, oceanography, underwater research, coastal ecology, marine technology, and ocean engineering.
FIGURE D.1 RESEARCH VESSEL Nautilus