Introduction to Design and Construction of Deep Manned Submersible “Harmony”

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Abstract

Deep sea exploration and exploitation are of an increasingly interest to human beings in the 21\textsuperscript{st} century. Manned and unmanned deep submergence vehicles are necessary means for deep sea explorations. In order to fulfill the requirements of deep sea explorations of COMRA (China Ocean Mineral Resources R&D Association), a deep manned submersible is developed in China and it is now named “Harmony”. The purpose of this paper is to briefly introduce the development process, including design, construction and open water tank test.

1 Introduction

Deep sea explorations are indispensable not only for the investigation of marine creatures, microorganisms, minerals and other resources hidden under the deep water, but also for the geophysical research into the structure and behavior of the earth. In the 21\textsuperscript{st} century deep sea exploration and exploitation are of an increasingly interest to human beings. Manned and unmanned deep submergence research vehicles are necessary means for deep sea explorations [1-6]. Under such a situation the Ministry of Science and Technology of the Chinese Government has approved a project to develop a deep manned submersible now named “Harmony”. China Ocean Mineral Resources R&D Association (COMRA) was appointed as the project coordinator and the final owner of this submersible. The development was formally started from 2003 and now its design, construction and open water tank test have been completed. The next stage is the sea trial test.

The purpose of this paper is to briefly introduce the process of development including design, construction and open water tank test.

2 Main Design Considerations

The missions set for this deep manned submersible are that it can fulfill the following tasks with a sea depth of not exceeding 7000 meters:

(1) To carry scientists, engineers and their various instrumentations and tools to the deep sea to perform tasks of oceanic geography, oceanic physics, oceanic biology and oceanic chemistry. With the excellent maneuverability, the submersible can locate the objective in the rugged benthal topography in the modes of hovering in the mid-water, or resting on the sea bottom.
(2) To investigate sulfide and cobalt encrustation resources. By means of underwater mini-drilling tools, the core sample of the cobalt can be obtained.

(3) To explore and locate the hydrothermal vent, to measure the temperature at the center of active hydrothermal vents, to take the water sample and keep it with constant temperature and pressure.

(4) To effectively perform the sampling of the deposits, suspended creatures and microbes at the required locations.

(5) To deploy the underwater devices in the specific locations, to inspect the cables and pipelines, and to perform other difficult tasks such as recovering wrecks.

The deep manned submersible is required to launch and work under sea state 4 and recover under sea state 5.

The principal particulars of the vehicle are given in Ref. [7]. The standard time required for one dive to the depth of 7000 meters is 12 hours in all, consisting of 0.5 hour each for launching and recovery, 2.5 hours each for descending and ascending and 6 hours for sea bottom work. The maximum survival time is 72 hours.

For deep sea manned submersibles there are not so many in the world and a comparison of this deep manned submersible with existing deep sea manned submersibles was also given in Ref.[7]. From the comparison one can see that the performances of this submersible are comparable with others. One of the specific features of this submersible is that it can work within 15 minutes under the condition of dynamic positioning, i.e. hovering mode.

Many efforts have been made in order to improve the hydrodynamic performance in the design of the deep manned submersible including molded lines, resistance analysis, hydrodynamic layout, maneuverability, descending and ascending without power supply, etc.

The submersible’s main body looks like a spheroid. As the shapes of viewports and manipulators are special, the lines at these locations are smoothed and optimized. The results of model tests in towing tank showed that the resistance and effective power of the submersible meet the design requirements.

Submersible’s stabilizer fins are arranged in the form of X type. The thrusters are distributed as different vectors. Four ducted propellers are main thrusters, which are arranged in the stern in the form of cruciform. The inclined angle of axes of propellers is 22.5°. There is a channel thruster in bow and one rotational ducted propeller in each broadside in the mid ship. With the control system implemented, the vehicle has the capability of space motion with six degrees of freedom.

The submersible has excellent maneuverability. We have carried out restricted model tests in wind tunnel and rotating-arm basin and built the mathematical model for six degrees of freedom movement. The submersible’s maneuverability is evaluated using the hydrodynamic force coefficients measured in the model tests and it is found that the maneuverability requirements are satisfied.

In order to save the energy, the descent and ascent is designed without any energy supply. In order to check the performances of these movements, we have established a mathematical model for steady state and
carried out the computer simulations. Through simulation, the locations and the weight for solid ballast are determined. The design is also validated through model tests.

As is well known, the general arrangement is to deal and assign all the functions and equipments, properly coordinate all kinds of the contradictions, locate all parts and adjust them in order to satisfy all the design specifications.

In order to do the general arrangement, the potential operating environment including temperature and salinity variations in the sea must be known. We have collected many data available to us and carried out some analysis, then the design environment conditions are specified for the submersible.

The general operation of the submersible is divided into eight steps: preparation, launching, diving, cruising, working, ascending, recovery and maintenance. The detailed tasks needed to be finished at each step are specified and allocated to specific personnel. These form the operation and maintenance document which also provides detailed instructions for some special operations such as hovering, climbing and landing on the sea bottom.

The design target of the general arrangement is to let the submersible have better performances, higher reliability, maintainability, and expansibility. We realized this target through partitioning into several modules according to the different functions and locations. After repetitive compromises and coordination, the locations for all components of the submersible have been determined. We have checked through a full scale model that it is compact enough and suitable for the submersible’s lines form. And in every important operating mode, the weight, buoyancy, stability, and posture of the submersible can be controlled within the design requirements.

We have put particular attention on whether the submersible can be assembled and maintained conveniently. The space is used to the greatest extent. The equipments can work in the appropriate surroundings avoiding disturbing each other and satisfy the demand of emergency safety.

In addition, the arrangement in the manned sphere is people oriented. Taking the characteristics of the sphere shell and different duties for the three persons into consideration, the design provides a comfortable solution to operation, observation and relaxation.

The main spherical pressure hull (radius 1050mm) is made of 12 separate side sections (lobes) and 2 bottom sections of spherical shape. The side and bottom sections were forged from flat plate blanks of specially chosen configuration. The welded hemispheres were placed into a special oven for thermal treatment to relieve residual stresses and eliminate distortions due to machining of the hemispheres. Manual TIG welding was used and the assembly and welding sequences were selected carefully to minimize welding and assembly deformations. Each weld was inspected by three methods: fluid penetration, X-ray and ultrasonic. The wall thickness offset is no more than 1mm, and the spherical shell offset from the correct shape is no more than 4 mm.

The design safety factor of the main pressure hull is 1.5, and the actual weight/volume ratio is 0.96 (including access hatch cover with its drive mechanism, brackets and windows).
Conical hatch and windows design is one of the key technologies for manned pressure hull design. The optimized geometrical dimensions of the hatch coaming can make the hatch deformed compatibly with the cover under work pressure to keep the access hatch cover sealing well. Peak bending stresses should be avoided. We have solved this problem through repetitive finite element analyses.

Three hydrostatic pressure tests were carried out to examine the fabricated manned pressure hull performance. They are:

- Hydrostatic test under trial (test) pressure of $P_{\text{test}} = 78\text{MPa}$ with 1-hour exposure under the pressure. This test was to check the structure strength and sealing ability under 1.1 times of service pressure.
- Long-term hydrostatic test under service pressure of $P_s = 71\text{MPa}$ with 8-hour exposure under the pressure. In this test, the pressure rising and decreasing rates were equal to the actual submersible rising and decreasing speed. The exposure time under 71Mpa pressure was equal to submersible’s working time. The stress distribution and the windows creep speed indicated the actual working condition.
- Cyclic testing under pressures varying within 0 to 71MPa, 6 cycles.

All of the test results indicated that the stress distributions were in well agreement with the design calculations. The sealing ability was very well. No plastic deformation was found.

The main framework is a welding space frame structure. Fabrication of such a titanium alloy structure is not an easy task. Large of welding tools set up were designed and welding sequences were selected carefully to reduce the welding deformations and to minimize residual welding stresses. Delayed cracks are easy to produce with high residual welding stresses for titanium structure. All of the main components of the framework were thermal treated.

The dynamic amplification factor of the framework in the design was taken as 2.0, and the safety factor was taken as 3.0. Strength and rigidity check included three typical working conditions, launch, recovery and fixed on the mother ship. Because the framework has a high rigidity requirement to avoid extrusion among the equipments, most of the components work in a low stress level. But the welding nodal points are exceptions. Delayed cracks are easy to occur in those joint regions. So those transition regions were highly taken care during design, manufacture and maintenance phases.

The framework was tested with two times of the equivalent actual loading distributions. This test was to simulate the recovery working condition. $450\text{KN}$ force was applied on the framework. The test results indicated that the stress distributions were in well agreement with the design calculation results. The maximal stress was no more than 200MPa. And the vertical deformation was no more than 10mm.

As a key for submersible navigating and working underwater, the navigation and communication system has several important functions including the communication between the submersible and its support ship, the guidance, navigation and control of submersible, the underwater exploration and so on.

The communication system of the 7000m submersible consists of two parts, namely, the surface communication and the underwater communication. With regard to the former, the submersible contacts its
support ship by VHF radio when it rises up to the surface. It communicates the ship by acoustics transferring audio, image and text information in the other case. Many difficulties in vertical long-distance transmission of acoustic signal, data compression and anti-jamming technique have been overcome during the development process. The effective transmission distance of signal being up to 10 km, the bi-directional transfer of audio and text information and the transfer of image from underwater to surface are reached completely.

There are two major methods for navigating the submersible. Under normal conditions, the navigation depends on a long-distance ultra-short baseline acoustic array mounted on the support ship and a transponder on the submersible. The position of the submersible relative to the ship is calculated using the distance between the sonar array and the transponder. Consequently the submersible’s geographic position is calculated from the relative position and the information from the DGPS on the support ship, which is transferred to the submersible by acoustics then. The combination navigation is designed to be laid on the submersible. It can estimate the submersible’s position relative to a given starting point by time integral according to the information from motion sensors, Doppler sonar, fiber gyroscope and depth sensor. If the long-distance ultra-short baseline sonar and acoustic system are in working order, they are used as the first navigation system and update starting point for the combination navigation system. However, the combination navigation system will be adopted in case of emergency in the long-distance ultra-short baseline sonar or acoustic system.

The navigation control comprises maneuver control and automatic control. The maneuver control takes charge of translating the commands by operators into input signals for the thrusters to maneuver the submersible in accordance with the submersible’s hydrodynamic characters and the thrusters’ performances. In the automatic control, the position and attitude of submersible being continuously fed back by special sensors and the current operation command is input to a digital computer all together. The computer deals with the information and command to form the input orders for thrusters to keep or change the submersible’s pose automatically. On the HOV, there are controllers of heading, depth (or height) keeping, pitch angle and hovering, which improve the navigation capability of submersible greatly and lighten operators’ burden.

The submersible is equipped with very complete detection equipments. Eight underwater lights are mounted on the submersible, in which there are four quartz halogen lights, two HID lights and two HMI lights. They ensure the lighting scope from the bow of submersible extending more than 15 meters. Five video cameras and still cameras are distributed around the bow to provide operator Omniperaing image information. The imaging sonar to detect barrier has a maximum extension of 200 meters. The bathymetric side-scan sonar on the submersible can detect a great variety of little objects with different landforms being taken in everything in a glance. At the same time, Doppler sonar is used to detect the velocity of flow and 7 ranging sonars are mounted on the submersible.

In order to have the advanced sampling ability in deep-sea, the submersible is equipped with two 7 functions manipulators, a sediment sampling implement, five hot liquid sampling implements and a sub-sea drill. Thus, the operator can control the sampling implements neatly to realize special functions, cobalt rock drill, hot liquid sampling, and sediment sampling. Then it can use these special heat preservation and pressure maintenance functions to realize safe and reliable fidelity sampling.

The normal ballast releasing and emergency jettisoning system consists of the jettisoning devices for
manipulators, power battery case and releasable ballast respectively. Being special to deal with all kinds of accidents or urgencies when the submersible navigate or work underwater, the first and second sets are able to make the submersible to rise to the surface as fast as possible by releasing weights in order to ensure the operators personal safety and protect main equipments. The last jettisoning device adjusts the submersible buoyancy, changing the descending/ascending speed by discharging the solid ballast. The last jettisoning device will also be first used in the emergency states.

It is possible for the manipulators to be caught by a net or some other obstacles when it navigates underwater. A special device to abandon the manipulators is designed at the fixing points of the manipulators to submersible. When this situation occurs, the jettisoning of manipulators will be executed by cutting off their hydraulic hoses and fixed bolts to free the submersible.

Abandoning the power battery case has an important effect on the stability and attitude of submersible. Hence it is adopted as a last resort only if a leakage appears in the pressure hull and other ballasts cannot be jettisoned. The cables of power battery case must be cut off by a special hydraulic instrument before the electric explosion bolts are detonated to release the power battery case, which can increase approximately 600 kg buoyancy for the submersible.

The releasable ballast system insures that the submerging and surfacing of submersible can be carried out normally. It is required to release a part of weights to reduce the weight of the submersible when the submersible submerges down to seabed. Releasing further these remaining weights make the submersible have enough buoyancy to return to the surface when it prepares surfacing from the bottom or in an emergency condition. These ballasts can be released by electromagnet or hydraulic driver. They can either work solely or be combined to finish the jettisoning, which is effective to improve the probability of success.

More than 20 tests have been conducted during the whole system development. The primary tests are: 1) the cutting force test of the hydraulic hoses; 2) the functional test of the anti-jamming ability of hydraulic cylinder releasing ballast in land; 3) the functional test of the differential hydraulic cylinder releasing ballast under the environmental pressure of 71.5 MPa; 4) the functional test of the releasable ballast jettisoning with the pitch angle of ±30° and the roll angle of ±15° in land; 5) the functional test of the emergency jettisoning of main battery case with the pitch angle of ±30° and the roll angle of ±15° in land; 6) the acceptance test of releasable ballast for its release function under the environmental pressure of 71.5 MPa; 7) the acceptance test of the emergency jettisoning of the main battery case for its release function by the electric explosion under the pressure of 15 MPa. This pressure is chosen because of the limit of the pressure tank; 8) the acceptance test of the hydraulic hoses and fixed bolts of manipulators being cut off under the environmental pressure of 71.5 MPa; 9) the acceptance test of the cables of the main battery case being cut off both in land and under the environmental pressure of 71.5 MPa. Through a series of tests, not only the required data are obtained, but also the functions of the three sets of jettisoning system are validated.

3 Construction

The purpose of the general assembly of the manned submersible is to assemble and integrate the submersible hull, frame, equipment, outfitting, pipes and cables into a complete submersible body system on a titanium framework.

A special architectural system has been set up for the construction work. A performance plan for the general assembly was made before the technological designing of the parts and equipment installation. The assembly and integration of the parts and equipment was the final step. The architectural system consists of a technical group, a construction group, a quality inspection group and a weighing group, with a special safety officer responsible for the in-situ safety supervision. The architectural system takes charge of the technical support of the general assembly, supplies various technical materials required by the general assembly, explains the design patterns and technical documents and confirms the part assembly technologies. In case any problem arises between the design and the assembly during the general assembly,
the architecture will have an active consultation with the designer to find a solution.

In accordance with the 36 installation items, its corresponding patterns, the installation technological documents, the inspection methods and criteria made on the basis of the patterns and technological documents listed in List of Checking and Inspection Items of Submersible General Assembly previously drawn up. The qualified inspector makes check and inspection on each item with validated measurement equipment and records the inspection data in the in-situ record table. Based on the in-situ inspection record, an inspection conclusion is made and recorded in Assembly Record Table of Manned Submersible Equipment, which is confirmed by the designers, quality inspectors and the chief architecture before the next stage of land joint commissioning.

The main difficulties in the general assembly consist of the following:

(1) The buoyancy blocks interfere with the frames, equipment and the cables during the assembly. The buoyancy blocks are manual modified at the site while all the titanium supports for the buoyancy blocks are manually modified to match the frame dimensions or the fit in well with the interface. Therefore, there is a great amount of modification work at the site.

After the exterior buoyancy blocks have been adjusted to the required positions, the support for fixing the buoyancy blocks and the frames are to be welded. Therefore, welding deformation of the buoyancy block supports should be also be considered to avoid inability of the fastening bolts of the buoyancy blocks to be screwed into the nuts of the buoyancy blocks. For this, repeated discussions have been made with the welder, who has also made trials. Finally, the welding deformation has been controlled through reduction of electric current and adoption of both sides skip welding.

(2) During the assembly of the light hull, the left and right parts of a head subsection was large in area, heavy in weight and complex in lines and had to match the groove pipe, the assembly of which became very difficult. The designer and the architectural system personnel agreed to modify the two parts. At the position of 1280 waterline (i.e. the central position of the co-observation window), the light hull was divided into two before being removed and manually divided by sawing slowly. No deformation happened after the light hull was separated. Such a treatment has finally solved the complicated assembly problem of the two light hull subsections.

(3) The accuracy required for the assembly of some sonar equipment like bathymetric sidescan sonar energy converter, Doppler velocimeter, motion sensor is very high. To meet such a high requirement, many methods have been considered and special tools have been made.

After the general assembly, the measurement results of the weight, the center of gravity and the center of buoyancy matched well with the design results, showing that the weight control during the assembly stage has been successful.

4 Open Water Tank test

The tank tests of the manned submersible have been done at the open water tank of China Ship Scientific Research Center (CSSRC), the shape of which is similar to a pot, with a maximum diameter of 85m and a maximum depth of 15m. Beside the tank, there is a dock, with a length of 8m, a width of 8m and a depth of 8m. Above the dock is a building, installed with a traveling crane of 30 tons, which, together with the dock, is used for launching and recovering the submersible.

The submersible was manned during the water tank test. During the test, only safety has been ensured can the test be continued. Therefore, during the test, we adhered to the principle of Putting people first, safety first, made careful preparations, elaborate tests and scrupulous maintenance. For each test, the preparation, the test process and maintenance have been done in strict compliance with the stipulated operation procedures and have been fully recorded. The general operation procedure of the tank tests is composed of test preparation, land inspection, launching and surface inspection, project test, recovery and maintenance and tests in the water tank. The list of open water tank test and measurement items as well as the requirements to be reached are shown in Table 1:
<table>
<thead>
<tr>
<th>No.</th>
<th>Item Name</th>
<th>Requirements</th>
<th>Test Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Balance Test</td>
<td>Weight: 22.9 tons; Metacentric height: 9cm</td>
<td>Measuring weight and center of gravity; adjusting suspended state, measuring center of buoyancy</td>
</tr>
<tr>
<td>2</td>
<td>Measurement test of the maximum lifting fore of the submersible during water exit</td>
<td></td>
<td>Measuring the change of lifting force by using a traveling crane to simulate the sea recovering</td>
</tr>
</tbody>
</table>
| 3   | Performance test of the lift supporting system | Oxygen concentration: 17%~23% Co2: < 0.5%  
Pressure warning inside the cabin: 108.7±10kpa  
Humidity: <85% | Normal oxygen supply, emergency oxygen supply, breathing through oral-nasal mask |
| 4   | Functional test of communications equipment | Clear talk                                                                  | Inspecting VHF communication functions above the water and under the water |
| 5   | Water supply and draining test of the ballast water tanks | Water intake time: < 600 Seconds  
Drainage time: <100 Seconds | Water intake and drainage tests of the ballast water tank |
| 6   | Adjustable ballast supply and draining test | Water intake and drainage flow rate: >3 L/m                                  | Intake and drainage test of the ballast water tank |
| 7   | Pitch adjusting test                   | Max. speed by adjusting with mercury: 150/m; Total adjustment angle: ± 200  | Adjusting forward and backward pitches by using mercury; adjusting forward and backward pitches by using propulsion forces |
| 8   | Functional test of the submergence-emergence jettison mechanism | Normal functioning of submergence and emergence jettisoning                  | Submergence jettisoning test, emergence jettisoning test |
| 9   | Functional test of the observation equipment | Normal functioning of all equipment                                          | Functional tests of imaging sonar, video cameras and underwater lights |
| 10  | Anti-collision sonar performance test   | Normal realization of functions                                              | Functional tests of each anti-collision sonar |
| 11  | Doppler sonar performance test          | Consistent with the motion sensors after checking                            | Test to record speed by using Doppler with the submersible operating at a speed of 1 kn |
| 12  | Mooring propulsion force measurement test of the propulsion system |                                                                              | Measuring mooring propulsion force of the submersible moving forward, backward, up, down, left and right. |
| 13  | Manual operation control test through computer distribution of propulsion forces | Functions can be realized.                                                  | Commission of the submersible by moving forward, backward, emerging, submerging, moving left, moving right while turning left and turning right |
| 14  | Manual steering control test without using computer distribution of propulsion forces | Functions can be realized.                                                  | Forward and backward steering commissioning  
Emergence and submergence steering commissioning  
Turning right and turning left |
<table>
<thead>
<tr>
<th>No.</th>
<th>Test Description</th>
<th>Functions can be realized.</th>
<th>Accuracy:</th>
<th>Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Auto constant height test</td>
<td></td>
<td>+/-20cm</td>
<td>Constant height commissioning at various heights</td>
</tr>
<tr>
<td>16</td>
<td>Auto constant direction test</td>
<td></td>
<td>+/-10</td>
<td>Constant direction commissioning at various speeds</td>
</tr>
<tr>
<td>17</td>
<td>Auto constant depth test</td>
<td></td>
<td>+/-20cm</td>
<td>Constant depth commissioning at various speeds</td>
</tr>
<tr>
<td>18</td>
<td>Hovering control test</td>
<td></td>
<td></td>
<td>Commissioning hovering functions</td>
</tr>
<tr>
<td>19</td>
<td>Measurement test of the stopping slip at a speed of 1 knot</td>
<td>Slip distance: &lt;10m</td>
<td></td>
<td>Emergency stop test at a speed of 1 knot.</td>
</tr>
<tr>
<td>20</td>
<td>Landing test</td>
<td></td>
<td></td>
<td>Test of the complete landing process</td>
</tr>
<tr>
<td>21</td>
<td>Functional test of manipulators</td>
<td>The manipulator movement of 7 degrees of freedom should satisfy the requirements.</td>
<td></td>
<td>Movement of the main and auxiliary manipulators, turning-on and turning-off of the manipulators;</td>
</tr>
<tr>
<td>22</td>
<td>Functional test of hydrotherm sampling</td>
<td>Correct communication between the manipulator interface and ICL signals; correct realization of sampling by hovering at the simulated spout or in the false steel bottom environment.</td>
<td></td>
<td>Simulating hydrotherm sampling process</td>
</tr>
<tr>
<td>23</td>
<td>Functional test of sediment sampling</td>
<td>Correct interfacing with the manipulators; correct realization of sampling movement in the false steel bottom environment.</td>
<td></td>
<td>Simulating sediment sampling process</td>
</tr>
<tr>
<td>24</td>
<td>Core sampling test of cobalt encrustation</td>
<td>Correction connection of electricity and liquid with the submersible; submersible stability during sampling, completeness of sampling core; reliability of emergency disengagement gear</td>
<td></td>
<td>Simulation test of core sampling of cobalt encrustation; disengagement test of core sampler</td>
</tr>
<tr>
<td>25</td>
<td>Functional test of whole procedures</td>
<td>Normal functioning of all equipment</td>
<td></td>
<td>Starting equipment operation according to Submerging Operation Procedures</td>
</tr>
<tr>
<td>26</td>
<td>Silver-zinc battery test</td>
<td>Electric voltage, current and capacity all meet requirements.</td>
<td></td>
<td>Test and inspection of power supply of the silver-zinc battery with all equipment working</td>
</tr>
</tbody>
</table>

Whole process test was conducted twice on Jan. 15, 2008 (the 50th) and Jan. 17, 2008 (the 51st). The test was composed of test preparation, land inspection, submersible lifting and docking, submersible leaving the dock for the tank center, water-filling of the ballast tank, movement test of manual operation with computer-distributed propulsion force and with non-computer-distributed propulsion force, pitch adjustment, auto constant-direction operation, auto constant-depth operation, auto constant-height operation, hovering hydrotherm sampling, functioning test of adjustable ballast system, functioning test of submersible landing, functioning test of anti-collision sonar, trim by stern, jettisoning, drainage ballast tank water and submersible recovery. All the missions in the whole process test have been successfully completed and all the test results have met the designed requirements. Fig.1 shows the test results of constant height, constant depth, constant direction and hovering mode.
Fig.1 Test results of constant height, constant depth, constant direction and hovering mode.

5 Summary

In order to fulfill the requirements of deep sea explorations of COMRA, a 7000m manned submersible is developed in China and it is now ready for sea trial test. In this paper, the development process, including design, construction and open water tank test have been briefly presented.

References

