# New Ceramic Pressure Hull Design for Deep Water Applications

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***Abstract*-Machines for deep-water application require pressure vessels in order to accommodate various type of units or human in the vessel securing them against the deep-water high pressure. In order to keep the machine to move freely in the water or on the bottom, the weight in the water should be as light as possible, and the pressure vessel must be fabricated as light as possible, keeping the pressure resistance capability.**

**Formerly, high strength steel was used for the material of the pressure vessel, but nowadays titanium alloy is the major material for pressure vessels of deep-water vehicles. Recently, ceramics has been applied for pressure vessel of ultra-deep water vehicle, namely, WHOI's HROV Nereus.**

**However, as ceramics are very brittle material, it must be designed with the greatest care, especially for the penetration.**

**Nereus is reported to have no ceramic penetration ports, instead, it has a hemispherical dome of titanium alloy which has several penetration ports. If the pressure vessel with penetration ports is made from ceramics, the underwater weight of the pressure vessel must become very light.**

**In order to solve this subject, a new concept was introduced for the design of ceramic pressure vessel, and ceramic pressure vessels were fabricated following this concept. Also one of them was laboratory-tested up to 118Mpa with success.**

**The basic configuration is a cylinder with two hemispherical caps at both ends, connected with ceramic flanges. There are two versions of the design; the first one with a transparent glass dome at an end of cylinder and the second one is with two hemispherical ceramic caps with penetration ports.**

**The key concept of the structural design under pressure is to let each part deform or shrink in natural condition without any restriction. Each part is connected with its partners, and when the deformation or shrinkage at the contact line with the partner is the same as that of the partner, no bending stresses shall appear anywhere.**

**To avoid the emergence of bending stress is critical for the brittle material as ceramics. This concept is applied not only on the connection of each part but also for the design of penetration port.**

**Glass dome application requires other great care to connect with ceramic cylinder. It is nearly impossible to adjust the displacements of contacting parts the same as each other because of the large displacement of glass dome due to the small Young's modulus, and slip happens or bending moment appears. In order to avoid bending moment to appear, a slip mechanism is introduced.**

**This paper discussed these new concepts for the design of ceramic pressure vessels.**

**Keywords: deep-water, ceramic pressure vessel, penetrations**

## I. INTRODUCTION

Pressure vessel is a key component for diving to deep. This component should be as light as possible in order to reduce the total volume and weight of the diving unit.

High strength steel had been the major material for this purpose, but because its specific gravity is large, other lighter metallic materials were used for the recent diving units, such as aluminum alloy or titanium alloy. However, there must be requests to reduce the underwater weight much more.

Engineering fine ceramics can answer this request, but great care has to be paid on the brittleness. WHOI's HROV Nereus has several pressure vessels made of ceramics, and it touched down the sea floor of the Challenger Deep of the Mariana Trench (10,912m deep). However, their pressure vessels have end caps made of titanium alloy in order for placing penetration holes. Also, every connecting surface of cylinder is covered with titanium alloy cover as a connecting flange. These are for securing the brittle ceramics from damage or collapse. This method shall be one of the best solutions. But if the pressure vessel is made from ceramics only, its weight shall become fairly light.

Underwater Technology Research Center is now working for development of Jellyfish catcher AUV working at 7,300m deep. In order to apply the ceramic pressure vessel to the vehicle, a scale model of the pressure vessel with 11,000m deep capability was made and pressure-tested up to 118MPa (the maximum pressure for the test tank), and then actual size of pressure vessel with 7,300m deep capability was made.

The feature of these pressure vessels is that there is no metallic connection cover and that it has a penetration hole without any support of metal. The scale model pressure vessel has another two penetration holes on the cylinder. But this design is not good because design criteria are not clear and also fabrication is too difficult, although it passed the pressure test.

Finally, the total weight and volume of the jellyfish catcher with safety factor 1.5 were calculated and the result showed the dry weight to be 72kg, volume to be 126.5liter, and buoyancy in sea water to be 58kgf.

## II. BASIC CONCEPT ON DESIGN OF CERAMIC PRESSURE VESSEL

The role of the pressure vessel is to keep its inside pressure to

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be one atmosphere or other intended low pressure against the large outside pressure. Thus, most part of the pressure vessel receives compression stress.

Engineering fine ceramics is a new material and this is very strong against the compression stress, but very week against the tensile stress and also week against the impact stress, although the mechanical properties of recent engineering fine ceramics are becoming very good. Thus, engineering fine ceramics is a good material to be used for pressure vessel on the viewpoint of compression stress (see Table 1).

Table 1. Comparison of various Ceramics

| Ceramics | Alumina | SiC | SiN | Zirconia |
|---|---|---|---|---|
| | A-601 | SC-1000 | SN-240 | Z-201N |
| Young's Modulus(GPa) | 380 | 440 | 300 | 200 |
| Density (gr/cm$^3$) | 3.9 | 3.16 | 3.3 | 6.0 |
| Compression Strength(MPa) | >2,350 | 2,500 | 3,820 | 5,690 |
| Poisson's Ratio | 0.23 | 0.17 | 0.28 | 0.31 |
| Fracture Toughness(MPa$\sqrt{\text{m}}$) | 5-6 | 2-3 | 7 | 4-5 |
| Thermal Conductivity(W/mK) | 34 | 200 | 27 | 3 |

*Material Number corresponds with Kyocera Inc., Japan

Another feature of the engineering fine ceramics is that its Young's modulus is fairly high. Some of them have Young's modulus over 400GPa while typical steel has Young' modulus of around 200GPa. Also it does not show plastic deformation. Its deformation is elastic until breakage.

These features introduce a new design concept: metallic pressure vessel for deep water application requires elastic-plastic deformation theory for the design, but ceramic pressure vessel needs only elastic deformation theory for the design, and it becomes very easy to design.

However, the engineering fine ceramics is very brittle, and special cares are requested.

Elements of the pressure vessel are shown in Fig. 1, and a cylinder and a hemispherical cap are easily designed and fabricated, but the problems to be considered shall be the follows:

(a) How to connect each cylinder? Is flange necessary? If necessary, how should the cylinder and the flange be designed?
(b) How to connect cylinder and hemispherical cap? Via flanges? How should the cylinder, hemispherical cap and the flanges be designed?
(c) The pressure vessel needs to have penetration port(s), and there rises stress concentration around the penetration port. How should the penetration port(s) be designed?

The answer to these questions is very simple: Keep the deformation of each cylinder or hemisphere as its natural deformation. Restriction should not be done.

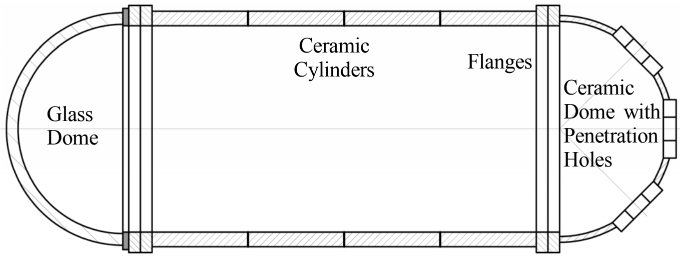


Fig. 1 Typical Configuration of Ceramic Pressure Vessel for Deep Water Application

## III. Details Of The Design Concept

### A: Nomenclature

$\ell$: Cylinder Length
$n$ : an index of buckling
$r$ : Radius of Cylinder or Sphere/Hemisphere
$r_c$ : Radius at the Center of Wall Thickness
$r_i$ : Inside Radius
$r_o$ : Outside Radius
$s_f$ : Safety Factor
$t$ : Wall Thickness
$u_{cyl}$ : Radial Displacement of a Cylinder
$u_{sph}$ : Radial Displacement of a Sphere or Hemisphere
$E$ : Young's Modulus
$P_k$ : Collapse Pressure
$P_o$ : Outside Pressure
$\varepsilon_z$ : Strain of Axial Direction
$\nu$: Poisson's Ratio
$\sigma_r$ : Stress in Radial Direction
$\sigma_\theta$: Stress in Circumferential Direction
$\sigma_z$ : Stress in Axial Direction

### B: Collapse Pressure Of A Cylinder

The basic collapse equation of a cylinder is shown in (1). The former half of the right side of the equation shows the buckling of a pillar, and the latter half of the right side shows the radial collapse of the cylinder.

$$P_k = E\left\{\frac{\pi^4}{n^4(n^2-1)}\left(\frac{r}{\ell}\right)^4 + \frac{n^2-1}{12(1-\nu^2)}\left(\frac{t}{r}\right)^2\right\}\frac{t}{r} \quad (1)$$

From this equation, two equations on collapse pressure of a cylindrical vessel are derived as:

$$P_k = \frac{E}{4(1-\nu^2)}\left(\frac{t}{r_c}\right)^3 \quad (2)$$

$$P_k = \frac{0.807E}{(1-\nu^2)}\frac{t^2}{\ell r}\sqrt{\frac{t}{r}} \qquad \ell \le 4.9r\sqrt{\frac{r}{t}} \quad (3)$$

(2) corresponds to a collapse pressure of an infinite length pipe, and (3) corresponds to a collapse pressure of limited length pipe with rigid flanges at both ends.

A cylinder designed by (2) is a part of infinite length pipe, and the deformation is the same at any point of the cylinder. Thus, two cylinders can easily been connected (permanent connection) without flanges.

A cylinder designed by (3) must have rigid flanges and/or stress support ring(s). Under high pressure, these flanges and/or rings shall obstruct the natural deformation of the cylinder as Fig. 2 shows, and bending shall happen on the cylinder. This is not a good situation for ceramics, and the pressure vessel shall be collapsed at lower pressure than expected.

For cylinder designed by (3), the wall thickness $t$ is given by the following (4) when the inside radius $r_i$ is given:

$$A = \left\{ \frac{4(1-\nu^2)P_k}{E} \right\}^{\frac{1}{3}} \qquad t = \frac{A}{1-\frac{A}{2}} r_i \tag{4}$$

*C: Collapse Pressure Of A Hemispherical Dome*

As is shown in most textbook on strength of materials, elastic collapse pressure of a sphere is shown as follows:

$$P_k = \frac{2E}{\sqrt{3(1-\nu^2)}} \left( \frac{t}{r_c} \right)^2 \tag{5}$$

Any part of this sphere receives the same compressive strength from any direction. For a hemispherical dome, stress distribution becomes the same as a whole sphere when the contact line of the counterpart deforms the same as the sphere. In other words, when the deformations of the hemisphere and the counterpart are adjusted, the hemisphere behaves as if it is a part of a whole sphere, and is expected to show its maximum pressure resistance. When a strength support ring or flange is attached on the hemisphere, deformation changes from its natural one, and will have bending stresses to collapse as shown in Fig. 2.

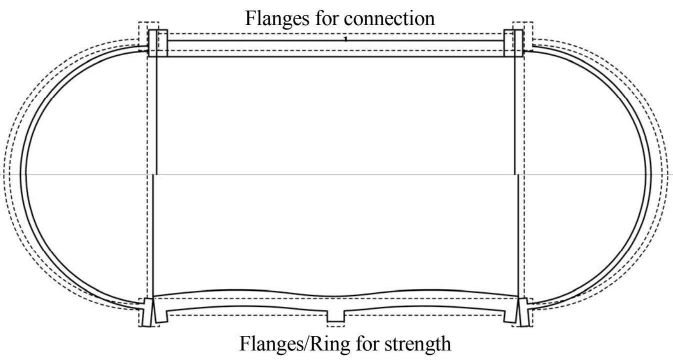


Fig. 2 Reinforcement Rings/Flanges and Deformation of Pressure Housing

Properly adjusted flanges for connection only will make the pressure vessel shrink evenly (upper half), but rings or flanges for strength support will give uneven deformation to the pressure vessel (lower half), and will make crack at the edge of contact line or where bending moment appears..

*D: Deformation Under Pressure*

As is shown in most textbook on strength of materials, the deformation of a cylinder and sphere under pressure are shown as follows assuming the internal pressure =0:

*D-1: Cylinder*

The radial displacement of a cylinder is shown as:

$$u_{cyl} = -\frac{r_i r_o^2 P_o}{E(r_o^2 - r_i^2)} \left\{ (1-2\nu)\frac{r}{r_i} + (1+\nu)\frac{r_i}{r} \right\} \tag{6}$$

The axial strain of a cylinder is:

$$\varepsilon_z = -\frac{(1-2\nu) r_o^2 P_o}{E(r_o^2 - r_i^2)} \tag{7}$$

Radial ($\sigma_r$), circumferential ($\sigma_\theta$), and axial ($\sigma_z$) stresses are:

$$\sigma_r = -\frac{\left(\frac{r_o}{r_i}\right)^2 - \left(\frac{r_o}{r}\right)^2}{\left(\frac{r_o}{r_i}\right)^2 - 1} P_o \tag{8}$$

$$\sigma_\theta = -\frac{\left(\frac{r_o}{r_i}\right)^2 + \left(\frac{r_o}{r}\right)^2}{\left(\frac{r_o}{r_i}\right)^2 - 1} P_o \tag{9}$$

$$\sigma_z = -\frac{\left(\frac{r_o}{r_i}\right)^2}{\left(\frac{r_o}{r_i}\right)^2 - 1} P_o \tag{10}$$

The stresses (8), (9), and (10) of the designed cylinder must be so confirmed that they are under the allowed level of the material.

*D-2: Hemisphere*

The displacement of a hemisphere is shown as:

$$u_{sph} = -\frac{r_i r_o^3 P_o}{E(r_o^3 - r_i^3)} \left\{ (1-2\nu)\frac{r}{r_i} + \frac{1+\nu}{2}\frac{r_i^2}{r^2} \right\} \tag{11}$$

Radial ($\sigma_r$) and circumferential ($\sigma_\theta$) stresses are:

$$\sigma_r = -\frac{r_o^3 P_o}{(r_o^3 - r_i^3)} \left( 1 - \frac{r_i^3}{r^3} \right) \tag{12}$$

$$\sigma_\theta = -\frac{r_o^3 P_o}{(r_o^3 - r_i^3)} \left( 1 + \frac{r_i^3}{r^3} \right) \tag{13}$$

*E: Design Procedures Of Cylinder And Hemisphere*

As the weakest part of the pressure vessel is the cylinder, every particular of the cylinder must be determined at first.

By giving the designed maximum operation pressure ($P_o$), design safety factor ($s_f$), and inside radius ($r_i$) of the cylinder, the wall thickness ($t$) is derived from (4) where $P_k = s_f P_o$. This gives $r_c$ and $r_o$ also.

Next step is to design the hemisphere. The target is to eliminate any type of bending stresses on both the hemisphere and the cylinder.

In order to do so, the radius of the wall thickness center circle of the hemisphere shall be determined as the same as that of the cylinder. Also, the wall thickness shall be so determined that the radial displacement obtained by (11) becomes the same as that of the cylinder at the same pressure loading. By this design, the wall thickness centers of both the cylinder and the hemisphere are anytime in coincidence with each other under the same pressure loading. This makes the bending stress not to appear.

The stresses (12) and (13) of the designed hemisphere are also confirmed that they are under the allowed level of the material.

This process gives thicker wall than that obtained from (5), the equation of elastic collapse of a sphere. However, the volume and weight of these thick wall hemispherical part are small compared with the other part of cylinder, and it has only a limited effect on the total volume and weight of the pressure vessel.

### F: Design Procedure Of A Penetration Hole On A Hemispherical Dome

Penetration hole causes stress concentration around the hole. The stress concentration coefficient will be 2 for a hole on sphere or hemisphere under pressure loading. However, the stress concentration is not a critical issue for the design.

The target of the design is to avoid collapse. A great care has to be paid on the displacement of the hole edge to behave as if the hemisphere does not have any hole as shown in the introduction.

The hole will have a short cylindrical coaming, and this coaming shall be so designed that the displacement (shrinkage) of the outer surface is just the same as that of the hole edge of the hemisphere as if it has no hole. The design parameters of this short cylindrical coaming are outer and inner radii and its length. These parameters are so selected as to fit the design concept. The edge of the lower end of the coaming will coincide with the inside surface of the hemisphere as shown in Fig. 3. The top end of the coaming will be at least the same level as the top of the outside surface. Gradual thickening of the wall is not necessary. Rather it will disturb the natural stress distribution over the hemisphere.

It is very easy to put a penetration hole on North Pole of the hemisphere. But the penetration hole designed by this procedure does not have any effect on stress distribution over the hemisphere, and further penetration holes can be prepared on other places of the same hemisphere as shown in Fig. 1.

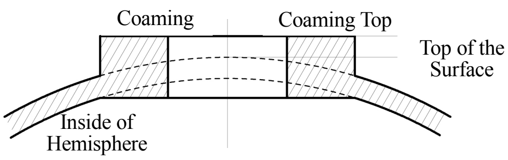


Fig. 3 Coaming on Hemispherical Shell
Bottom of the coaming starts from the inside surface of the hemisphere

### G: Design Procedure Of Flanges

Usually, the flange has two roles, one is for connection with the other parts and the second one is a strength support ring. However, the role of strength support ring is not good for such brittle material as the ceramics as shown in Fig. 2, and the role of the flange is only for connection with the other parts.

The outer radius of the flange has to be larger than that of the cylinder or hemisphere for fixing by connection gears. The inside radius of the flange shall be the same as that of the cylinder and the outside radius shall be so determined that the displacement of flange at the radius of the wall thickness center circle of the cylinder or the hemisphere become the same as that of the cylinder or the hemisphere.

Considering the flange to be a part of a cylinder, this calculation can be done by (6), and a material of smaller Young's modulus is required.

By this design, the cylinder, the flange, and the hemisphere shrink under the pressure loading without any discrepancies of the displacements with each other at the designated radius, that is, the wall thickness center circle of the cylinder and the hemisphere. Also there is no mutual restriction of deformation, and there happens no bending stresses on each part.

### H: Connection Of Cylinders, Hemispheres, And Flanges

Permanent connection of cylinders, hemispheres, and flanges can be done using adhesive glues. However, experience tells us that the glue on outer surface or in-between both faces under compression loading is very easily peeled off. So, it is essential to connect these parts at the inside of the pressure vessel. This can easily be done using a thin connecting plate (joiner) and adhesive glue.

The shallow water sealing shall be done at the surface connection line by pasting soft sealant. The deep water sealing shall be realized by the face-to-face contact of the edge of each part by strong pressure.

The temporary connection can be done by flanges. The bolt holes on flange may change the deformation characteristics of the flange. Instead, vise-like gears can be used very easily to fix up the two flanges. Groove at the rim can be used for O-ring setting. Application of sealant to this coupling is not recommended because this resin is very difficult to peel off after the decoupling of the flanges

### I: Design Of Glass Dome Support And Flange

When a camera is planned to be installed in the pressure vessel, a transparent viewport becomes necessary. For deep water application, a transparent glass dome is a good part for view port. However, special care should be paid to its Young's modulus. It is 64GPa and this is only 1/3 of the conventional steel. This means that the design by paragraph "*E*" gives unrealistically thick wall glass dome. In order to select thinner wall glass dome, some slipping mechanics is required, otherwise the glass dome shall be bent and crack shall happen.

Thus, a new mechanism is introduced; a glass dome is mounted on the metallic seat and they are bonded by glue at the inside of the dome. Outside of the dome is sealed by sealant as for shallow-water-sealing. This metallic seat is mounted on a ceramic flange and moored to the flange via many mooring threads to allow the displacement (shrinkage) of the glass dome by sliding. In order to make the frictional coefficient as small as possible, DLC (Diamond-Like Carbon) coating may be planned

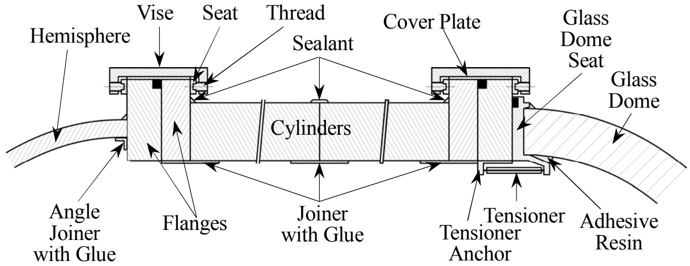


Fig. 4 Schematic drawing of the Connection Method

on the contacting surface of the metallic seat with the ceramic flange. O-ring shall be prepared at the rim of the metallic seat for shallow-water-sealing. Fig. 4 shows the schematic drawing of the connection methods of each part.

There may be some cases where metallic hemispherical cap is applied to the ceramic cylinder. Most cases, the rigidity of the metallic cap is not enough to adjust the displacement with the ceramic cylinder. The sliding mechanics can be applied to this combination also.

## IV. Application To A Scale Model Of Pressure Vessel

Following the above mentioned consideration, a scale model ceramic pressure vessel was designed, fabricated, and tested at 118MPa which is equivalent to 11,000m water depth, the maximum water depth in the world.

The pressure vessel had two viewports on the cylinder for three dimensional viewing by TV camera.

The cylinder and the hemispheres are made from Silicon Nitride ceramics (SN-240), and the flanges are made from Zirconia (Z-201N). One of the hemispheres has a penetration hole for electric communication. As the scale model of the flange is small to fit the actual O-ring, so instead of preparing a groove for O-ring, the sealing was done by pasting sealant on the joint line of the flanges.

The coamings of the port holes on the cylinder wall of the scale model pressure vessel were planned with the even length ellipsoidal cylinder considering the difference of stresses of axial and circumferential directions, but it was changed to a rectangular pillar with round hole at the center because the machining system cannot be applied to the complicated curved surfaces. The stress and strain analyses were also beyond the manual calculation and were done by numerical method, confirming that the stresses were within the allowable range.

The port holes were planned to have hemispherical glass domes, but the model was too small to apply glass dome. So, steel domes were applied. Fig. 5 shows the scale model pressure vessel where white ones are flanges made from Zirconia, and Table 2 shows its principal particulars.

The scale model pressure vessel finally survived the pressure test up to 118MPa.

Fig. 5 Scale Model Pressure Vessel
Cylinder Length：252mm
Inside Diameter: 90mm

Table 2. Principal Particulars of Scale Model Pressure Vessel

| Part | ID | OD | Length/Thickness | Material |
|---|---|---|---|---|
| Cylinder | 90 | 104 | 252 | SN-240 |
| Cap | 94 | 100 | | SN-240 |
| Flange | 90 | 114 | 6 | Z-201N |
| Penetration | 16.5 | 27 | | |
| Dummy Viewport | 25 | 27 | Hemisphere | SUS630 |

## V. Application To An Underwater Robot

Utilizing these design concepts, a new pressure vessel of a 7,300m-AUV was developed. This has a glass dome for TV camera viewing. The body (cylinder and a hemispherical cap) is made from Silicon Carbide ceramics (SC-1000) and the flanges are made from Silicon Nitride ceramics (SN-240). The SC-1000 was selected because of its very high Young's modulus, large compression strength, small specific gravity, and large heat conductivity necessary for installation of PCs in the body. The SN-240 was selected because of its moderate Young's modulus for flange design and its toughness and small specific gravity. The 4 0.3m-long cylinders are connected to a 1.2m long cylinder using a method shown in paragraph "*H*". The flanges are also fixed to the cylinder or hemisphere as discussed in paragraph "*H*". Caps and cylinder are jointed using vise-like fittings so that no scar may happen. O-rings for shallow water sealing are inserted in-between these flanges.

As for the penetrator, the detailed design of electric/optical lines is not yet fixed, and there is only a block of titanium alloy cap.

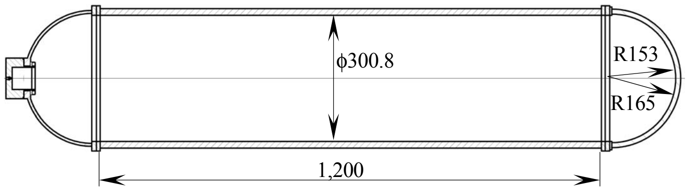


Fig. 6 Concept drawing of New AUV with Ceramic Body
Maximum Operation Depth: 7,300m
Weight in Air: 72 kgf
Weight in Sea Water: -58 kgf

Table 3. Principal Particulars of New AUV's Pressure Vessel

| Part | ID | OD | Length/Thickness | Material |
|---|---|---|---|---|
| Cylinder | 300.8 | 332.2 | 300x4pieces | SC-1000 |
| Flange | 300.8 | 346.2 | 9(Flat)<br>11(w/O-ring Groove) | SN-240 |
| Glass Dome | 306 | 330 | 12 | |
| Ceramic Cap | 309.4 | 323.6 | 7.1 | SC-1000 |
| Penetration | 60 | 98 | 15.4 | SC-1000 |

## VI. Closing Remarks

Engineering fine ceramics is a brittle material, and has not been used as a structural material. However, the characteristics of ceramics as structural material are improving very rapidly.

Ceramics is not strong against tension, but is very strong against compression. Also ceramics does not show plastic deformation. Thus, elastic design method can be applied within the allowable limit of compression strength. Elastic-plastic consideration is not necessary, and the design becomes very easy one.

Everything receives water pressure in the water, and this means that every part of the body is in compression except when the body is moving very violently. However, present underwater vehicles do not move violently. Thus, it is enough to consider the static water pressure.

Young’s modulus of ceramics is fairly high compared with metallic material, and also its specific gravity is very small. This means that pressure vessel with thin shell can easily be designed and fabricated, and its weight becomes very light. Thus, ceramics is a very good structural material for pressure housing of underwater vehicle.

What is necessary for further application of ceramics to the pressure vessel is the reliability. In order to establish the reliability, many applications of ceramic shells to various field operations will be necessary.