A pressure-neutral acoustic transmit receive module (PR-TRM) with integrated data processing for deep sea applications

M. Molitor, M. Moses, M. Schmieger, O. Walter, P. Weber, R. Lemor
Fraunhofer-Institute for Biomedical Technology IBMT
Ensheimer Str. 48
66386 St. Ingbert, Germany

***Abstract*- Hardware, i.e. electronics and sensors, have to be packaged in a special way to bear the heavy mechanical loads, which are encountered in deep sea applications. Expensive materials and pressure resistant housings are often used. Another way to fulfill the requirements is to use a pressure neutral (pressure tolerant) approach by casting the components into an appropriate material. This might be a hard elastomer to protect components like quartz oscillators which have gas filled voids against being crushed or a synthetic rubber that is used to enclose electronic boards to disperse the pressure over the complete surface (components and circuit board).**

A pressure-tolerant system has been developed that can be used to perform different ultrasonic measurements under deep sea conditions like the detection of obstacles, distance or flow metering, concentration & compressibility measurements, Doppler logging, side scanning or acoustic communication. Depending on these different applications high sampling rates and fast detection times as well as a real-time signal processing are required. PN-TRM is a pressure neutral single channel transmit-receive-module that can be used to a depth of 6000 m. 8 ultrasound transducers with frequencies up to 25 MHz can be connected by a multiplexer. The system is equipped with a DSP and can operate as a stand-alone system. The communication with an external PC can be done via different interfaces (CAN, ISA, etc.).

To ensure the operation under high pressure conditions, different parts of the circuit as well as the complete system were tested in a chamber that supports pressures up to 600 bar. Among pure mechanical pressure tests, quantitative functional tests (distance metering) were performed.

I. Introduction

Pressure tolerant equipment has been of great interest for the oil-well drilling industry since the early 1920s. Thus the beginning of deep sea exploration beyond a depth of 4000 m in the 1950s was pushed forward by the advances made in deep bore hole drilling. The success of Picard's descent into the Marianas Trench in 1960 was supported by the use of a pressure tolerant propulsion system initially developed for a drilling head [1].

In 1976 Barnes et al. have written in their extensive review on pressure tolerant electronics (PTE): *"Exploration and exploitation of the oceans will definitely increase. How much of the equipment needed in these tasks will utilize PTE will be up to the designer of the vehicles or instrumentation packages. He must demonstrate that PTE is cost effective. This effectiveness may be in terms of internal volume reduction of manned submersible, cooling load reduction ..."* [1]. At that time the focus of manned deep sea underwater exploration was more the discovery of unknown regions with a touch of adventure.

Today's interest in deep sea exploration is more and more becoming economically, driven by the search for raw material and energy resources. The average depth of the oceans is 3800 m which is also the current border for industrial explorations [2]. Brazilian and Mexican geologists expect significant oil in places beyond a water depth of 4000 – 7000 m.

These are regions which are completely unsuitable as practical working environments for humans. Instead of manually driven tools and equipment autonomous systems have to be used. Operation by remote control is possible, yet limited due to its technical complexity and the lack of fast communication links.

For a comprehensive and flexible operation, systems are required that fulfill several tasks with as low hardware (weight) and energy effort as possible. Concerning ultrasonic applications like the detection of obstacles, distance or flow metering, Doppler logging or side scanning, a multitasking platform like the TRM is of great advantage. For a comprehensive use not only in autonomous underwater vehicles (AUVs) but also in autonomous driven tools (ADTs) or subcomponents (ADSs) a pressure tolerant housing of TRM is of more advantage than a pressure resistant housing.

II. Pressure Tolerance vs. Pressure Resistance

As has been shown during the project *"Pressure tolerant systems for permanent submerged applications"* [3], a good solution for a pressure tolerant housing is the use of polyurethane or silicon to transmit the hydrostatic pressure to every component of the system.

A short comparison shall show that there is not only an advantage concerning the flexible application of the TRM in AUVs, ADTs or ADSs with pressure tolerant housing but also concerning costs and weight. The outer dimensions of the TRM are (220 x 100 x 40 mm). For a pressure resistant

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

housing with connectors a box is necessary which has the internal (unsupported [4]) dimensions of (225 x 105 x 40) mm. The largest dimension of the housing is relevant for the layout of the wall thickness necessary to withstand the outer pressure. The ratio between wall thickness ***t*** to the biggest internal dimension ***a*** of the housing for an external pressure ***p*** is given by equation (1), [4].

$$\frac{t}{a} = \sqrt{\frac{3 \cdot (3 \cdot m + 1) \cdot p}{8 \cdot m \cdot s_{max}}} \quad (1)$$

m is the reciprocal of Poisson ratio and s_{max} is the maximum stress at the center of the relevant wall of the housing .

Assuming that the thickness of the wall should not be more than one fourth of the length of the wall [4], figure 1 shows the thickness for the housing with a inner length of 225 mm. The material is stainless steel (17-4 PH) with a yield strength of 862 MPa (s_{max}) and a Poisson ratio of 0.3.

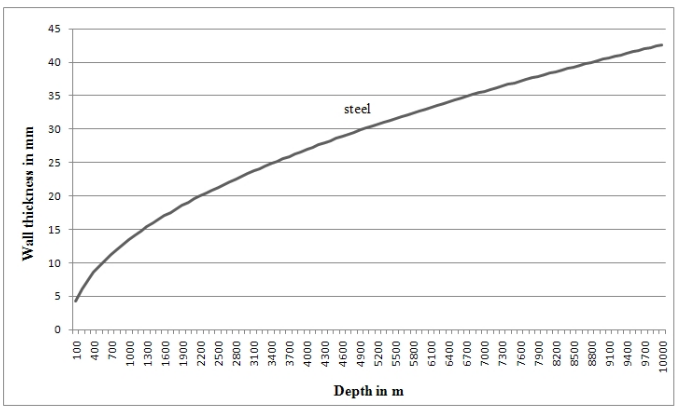

Figure 1. Wall thickness of the housing for stainless steel (17-4 PH).

For a depth of 6000 m a wall thickness of 33 mm is necessary. Figure 2 shows the relation between the material costs for the housing according to the dimensions given above as a function of the diving depth. Costs for the steel (density $7.6 \cdot 10^{-3}$ kg/m^3) were assumed to be 6 Euro per kg.

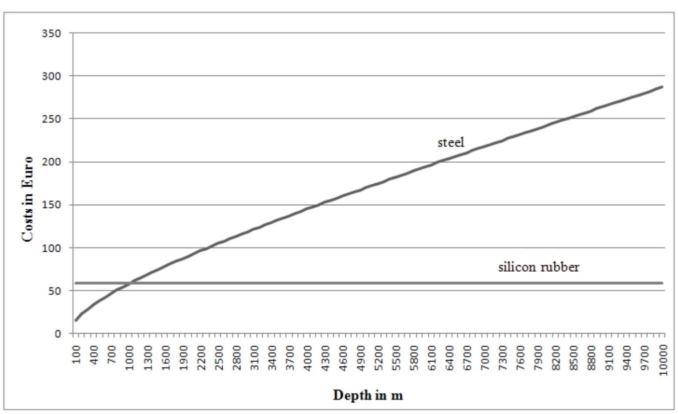

Figure 2. Comparison of the costs for pressure resistant and pressure tolerant housing.

For the TRM we have made very good experience by casting the electronic board with silicon rubber for pressure tolerance. Taking the dimensions for the silicone rubber block into account as the inner dimensions for the steel housing, the second graph in figure 2 shows the costs for the pressure tolerant housing (density 970 kg/m^3, 66 Euro per liter). Beyond a depth of 1000 m the pressure tolerant housing is more cost efficient than the pressure resistant housing.

A last look at the weight gives us information about the energy necessary to move the housing under water. Whilst the buoyancy force for both housings is nearly the same the driving force and hence the energy for moving it, is much bigger for the pressure resistant housing due to the outer dimensions.

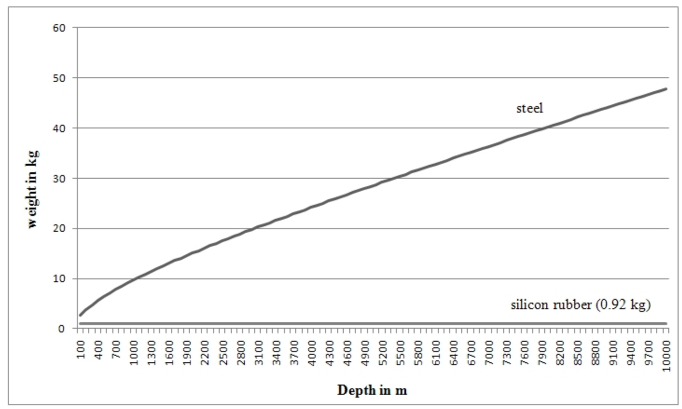

Figure 3 Comparison of the weight for pressure resistant and pressure tolerant housing

Of course this is only a general, simplified approach because an underwater system consists of more than only the electronic board. Additional cabling, sensors and power supply are necessary for the operation of the ultrasonic system TRM. The system itself is designed for carriers such as AUVs, ADTs or ADS.

III. TRM – Transmit Receive Module

TRM is a DSP based single channel ultrasonic measuring system for pulse-echo- or transmission operation. Figure 4 shows the block diagram of the system.

Different transmit signals (0 – 25 MHz) can be programmed through the waveform generator. The received signals are amplified (constant or time gain controlled), digitized (12 bit, up to 100 MSPs) and processed with a digital signal processor (Motorola 56311). Different programmable filters are provided for signal conditioning. The scan FIFO can fit up to 512 kB of data which is enough even for long A-Scans if an appropriate delay is considered. Different interfaces can be used to connect the module to other devices. By the use of a multiplexer up to 8 transducers can be connected to the module.

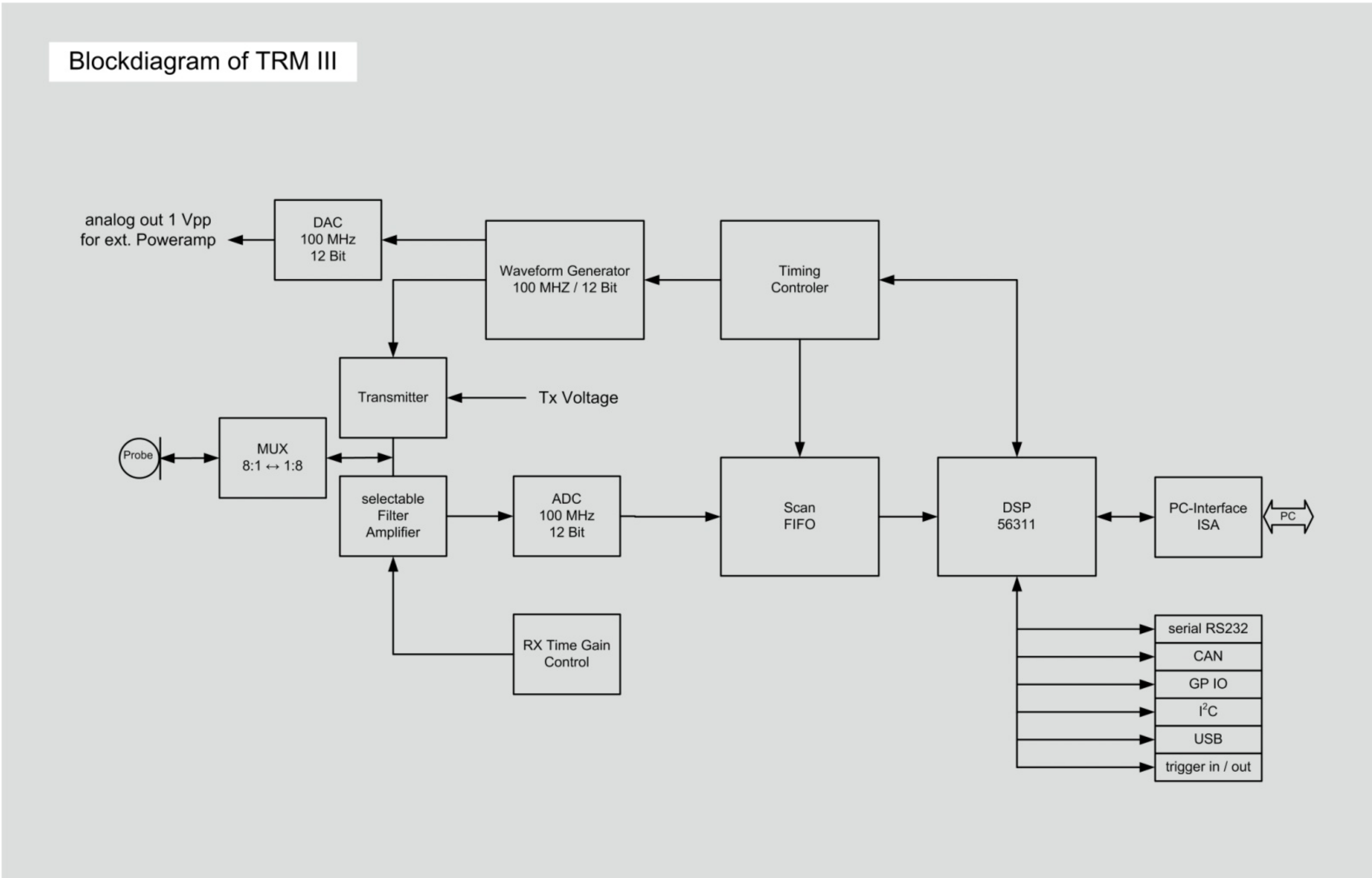

Figure 4. Block diagram of TRM

The TRM was designed as a general ultrasonic research and development platform for stand-alone and embedded applications like the measurement of time-of-flight, frequency shift or attenuation. Several implementations of the module were created during the past for level and distance metering, flow measurement (Doppler, Speckle Tracking, volume) and material characterization. As these are also typical measuring tasks in underwater applications the system was adapted for operating in depths down to 6000 m. To make its deep-sea-use as flexible as possible the concept for the housing was to make it pressure tolerant. According to the casting approach [3] the complete electronic board was embedded in a block of transparent silicon rubber under vacuum to avoid air inclusions. The dimensions of the rubber block were several millimeters larger than the dimensions of the board. Figure 5 shows the casted board. The cables for power supply (+12 V, ± 5V), for the transducers and for the interface (RS232) were also sealed with the silicon rubber without any additional duct. For the pressure tests the TRM was connected to an ultrasonic transducer (1MHz) which was fixed in a frame with a stainless steel reflector at a distance of 10 cm allowing for sound speed and compressibility measurements of materials. For validation and failure determination the system several functional tests were performed in a pressure chamber with pressures up to 600 bar.

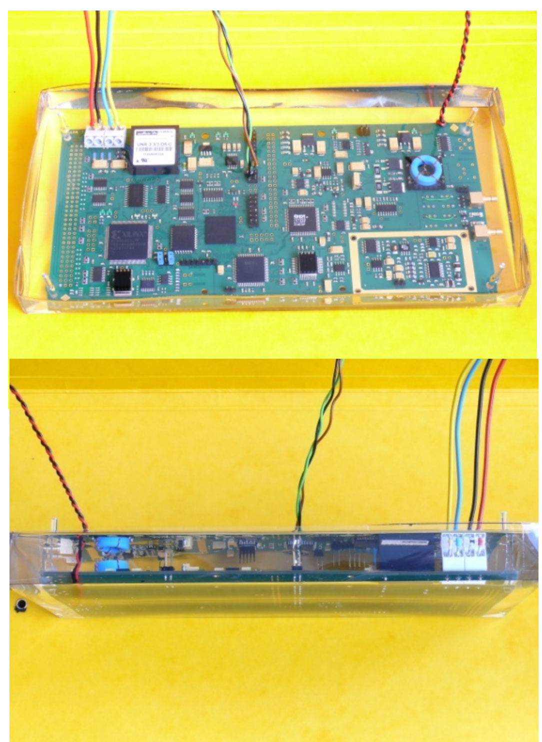

Figure 5. Casted TRM top view and side view.

IV. Pressure Tests

For the functional tests of the TRM the experimental setup described above was placed in IBMT's pressure chamber. This chamber has a volume of 385 ltr. and can be driven to a maximum pressure of 600 bar. Figure 6 shows the chamber together with the peripheral supply technology and measurement equipment.

Figure 6. Pressure chamber (diameter 440 mm, volume 385 ltr.) together with external measurement equipment.

On the top side the hull of the chamber has five pressure resistant grommets. Each of them is equipped with four contacts so that it is possible to perform functional tests with external electronic control. A special rack was designed that holds the casted TRM board and the frame with the two transducers inside the chamber.

After the rack was inserted into the chamber the external power supply (+12 V, ± 5V) was connected to the board. The serial interface (RS232) was connected to an external computer. The system was driven in pulse-echo-mode and the received echo from the reflector (A-Scan) was transmitted to the external computer via the serial interface.

After the chamber was closed and filled with water, the pulse-echo-measurement was started. Figure 7 shows the initial A-Scan received by the probe.

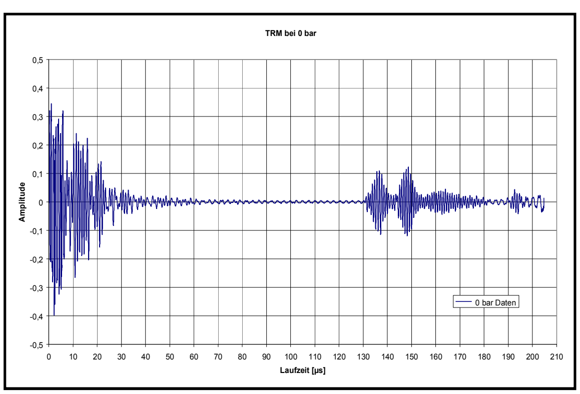

Figure 7. A-Scan at an initial pressure of 0 bar. After the initial ringing of the transducer the echo arrives after 130 µs.

During the tests the pressure was increased in steps of 50 bar to the maximum of 600 bar. Pressures were cycled multiple times between 0 and 600 bar. Figure 8 shows the expected reduction of the time of flight of the echo caused by the increase of the pressure from 0 to 50 bar.

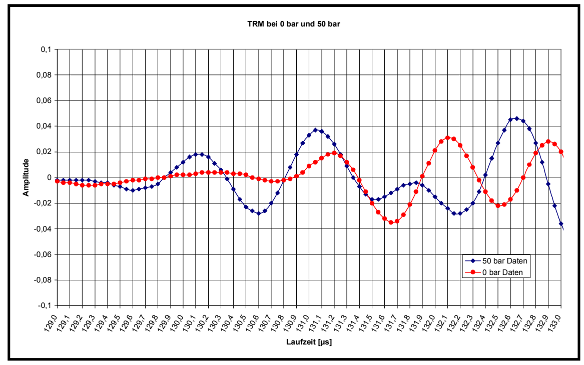

Figure 8. Reduction in time of flight of the echo caused by increase of the pressure (blue echo at 50 bar, red echo at 0 bar).

After the pressure tests the TRM board was electronically tested and visually examined for component failures. Components which showed functional failures or components which released gas (figure 9 top) or showed deformation were replaced by hard elastomer encapsulated components. (figure 9 bottom)

With this component encapsulation the TRM was tested in multiple pressure cycles (10) and long term pressure tests (72 hours) without any failure up to 600 bar.

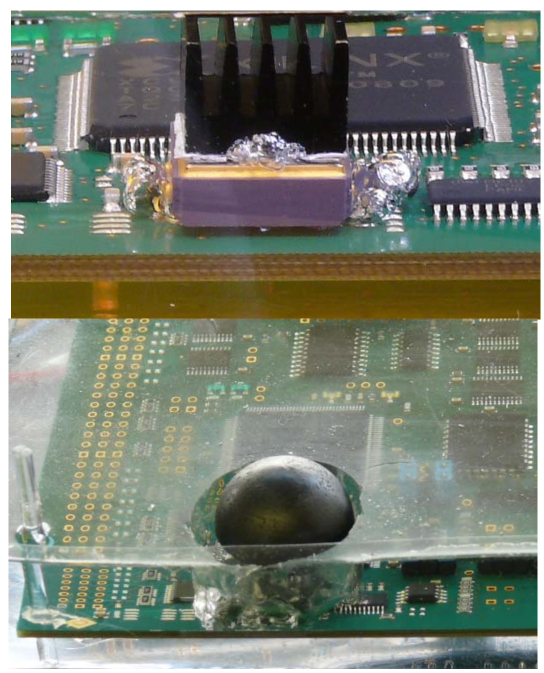

Figure 9. Top: Air bubbles in the cast released from the housing of a quartz oscillator. Bottom: Hard elastomer encapsulation of the quartz oscillator.

V. Temperature Test

To ensure stable operation of the TRM, the temperature distribution within the encasted system was measured. The experimental set up that was used in the pressure test was investigated with an infrared camera (Jenoptik, VarioScan 3021-ST HR) to visualize the temperature distribution. In long-term tests (20 h) the temperature was monitored. Figure 10 shows the temperature image mapped upon the TRM board. *Hot spots* could be observed at components such as the quartz oscillator, the AD converter and the voltage conditioning unit. After calibration of the infrared camera with the thermal conductivity of the encapsulation material, the component temperature was calculated. In all cases the component temperature was below 50 °C which is well within the component specification so that there is no risk for a thermal failure of the casted system.

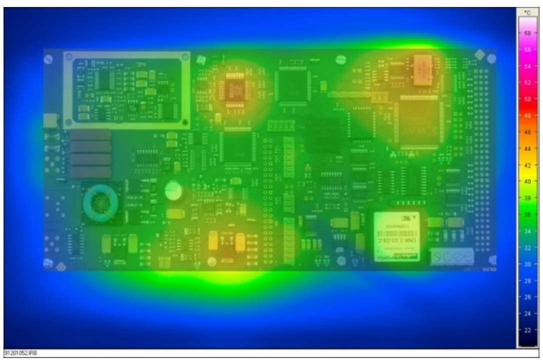

Figure 10. Temperature map of the casted TRM after 20 h of operation

VI. TRM User Interface and Signal Processing

The Transmit Receive Module TRM can be used as a standalone system with data logging or together with an external computer (e.g. laptop) which is connected via different interfaces (e.g. RS232, USB or CAN) allowing for a multitude of ultrasonic applications. Depending on the application, different graphical user interfaces (GUIs) and application programming interfaces (APIs) are available giving access to standard routines such as:

- Operation mode (pulse-echo or transmission)
- Parameter setting of the module (frequency, signal form and amplitude, sampling rate, amplification, TGC, filters, delays, receive windows, etc.).
- Configuration and operation of the multiplexer.
- Receive and display of single A-Scans.
- Processing of the received signal in time and frequency domain including correlation techniques, e.g. for precise evaluation of time of flight.
- Display and storage of settings, data and results.

Figure 11 shows a part of the GUI running on a laptop. For deep sea applications the system can operate as a stand alone system (e.g. salinity measurement or flow measurement with data logging) or controlled by a central unit (e.g. Doppler log and obstacle detection in an AUV).

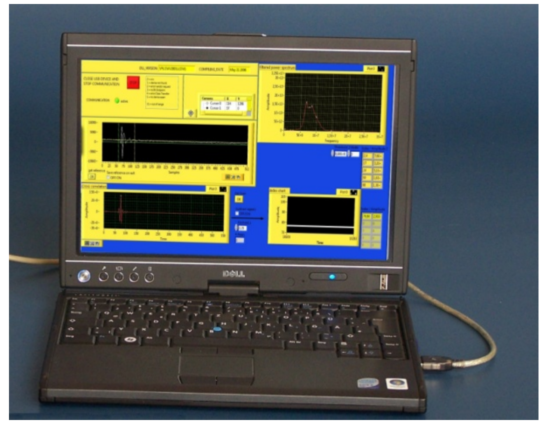

Figure 11. Graphical User Interface of the TRM

VII. Deep Sea Applications

The TRM and its derivates have been used in multiple ultrasonic applications under *normal pressure* conditions like distance metering (e.g. level), the detection of obstacles (e.g. parking control for cars), flow metering (e.g. heat meter), flow profiling (e.g. speckle tracking), material characterization (e.g. turbidimetry) and medical applications.

The pressure tolerant PR-TRM module allows for application of these ultrasonic techniques for deep seas operations. The system was successfully used as a stand-alone system for determination of material constants under varying pressures (i.e. speed of sound, compressibility) with ultrasonic frequencies between 500 kHz and 5 MHz and was successfully incorporated in an AUV as an obstacle detection system for distances between 0,5 and 15 m with a frequency of 400 kHz (TieTEK-Demonstrator). Further applications are being developed.

Acknowledgment

This work was supported by the Fraunhofer internal programs under grant number MAVO 819573 (TieTEK).

References

[1] Barnes H., Gennari J. J.: A Review of Pressure-Tolerant Electronics (PTE), Naval Research Laboratory, June 1976, pages: 38.

[2] Hautmann D.: Taucher der Extreme, Rheinischer Merkur, Janaury 2010.

[3] Thiede C. et al.: An overall Pressure Tolerant Underweter Vehcle DNS Pegel, Proceedings OCEANS '09 IEEE Bremen, ISBN: 978 - 1 - 4244 - 2523 – 5

[4] Sharp, A. G.: Design curves for oceanographic pressure-resistant housings, Technical Memorandum, 3, Issue 81, 1981.