FUTURE CO_2 CONTROL USING MEMBRANE GAS ABSORPTION ON BOARD HNLMS SUBMARINES (DEVELOPMENT UPDATE)

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Abstract
The NL MOD Defence Materiel Organisation has a cooperation program with national research institute TNO to develop a CO_2 Membrane Gas Absorption (MGA) system for HNLMS submarines. The system promises to achieve lower mean CO_2 concentration levels (down to 0.5 %) compared to current Sodalime canisters on board due to a better absorption process and larger capacity. The operational and logistical support will be significantly less as the system is regenerative and may operate continuously. Current canisters are relatively expensive items, require frequent replacement and bring about a considerable logistical effort.

This paper is an update of a paper presented at the SAMAP 2003 conference and describes the system development since then by both TNO and the NL MOD. The previous paper dealt with the subsequent project phases (proof of principle, proof of concept) and development work up to 2003. This paper presents a design that complies with RNLN requirements and fits on board HNLMS submarines.

Actual (size) data of the system including 3D pictures, dimensions and a list of components are available. The system is in the laboratory where it is undergoing test. Development work by TNO in the recent period was focused on achieving membrane stability. The CO2 binding salt in the working fluid crystallized and appeared to gradually block the membrane. Development work by the NL MOD is focused on the interfaces and integration with existing submarine systems. That includes the development of an experimental set-up to simulate CO2 injection into sea water.

In the gas absorption process, a membrane separates the working fluid from the submarine atmosphere. CO_2 passes through the membrane into the absorption fluid. The fluid is regenerated at elevated temperatures. The use of small size hollow fiber membranes results in a moderate volume requirement. Absorption (quality) fluid losses will be little, as previous experiments have shown that the fluid is more stable than other currently used fluids, e.g. monoethanolamine. The process is highly selective with a discharge of more than 99 % pure CO_2.

Introduction
Current CO_2 control on board HNLMS submarines uses sodalime canisters. Air is ventilated through the canisters and the lime binds CO_2 from the submarine atmosphere. Although the system is simple to operate and only requires energy for a ventilator, it is less effective at low CO_2 concentration levels. The well-being of personnel on board and avoidance of long term health effects (formulated in regulations becoming more stringent all the time) necessitate the RNLN to achieve lower levels on board her submarines. Current CO_2 concentration levels fluctuate between 0.5 and 1.5 %.

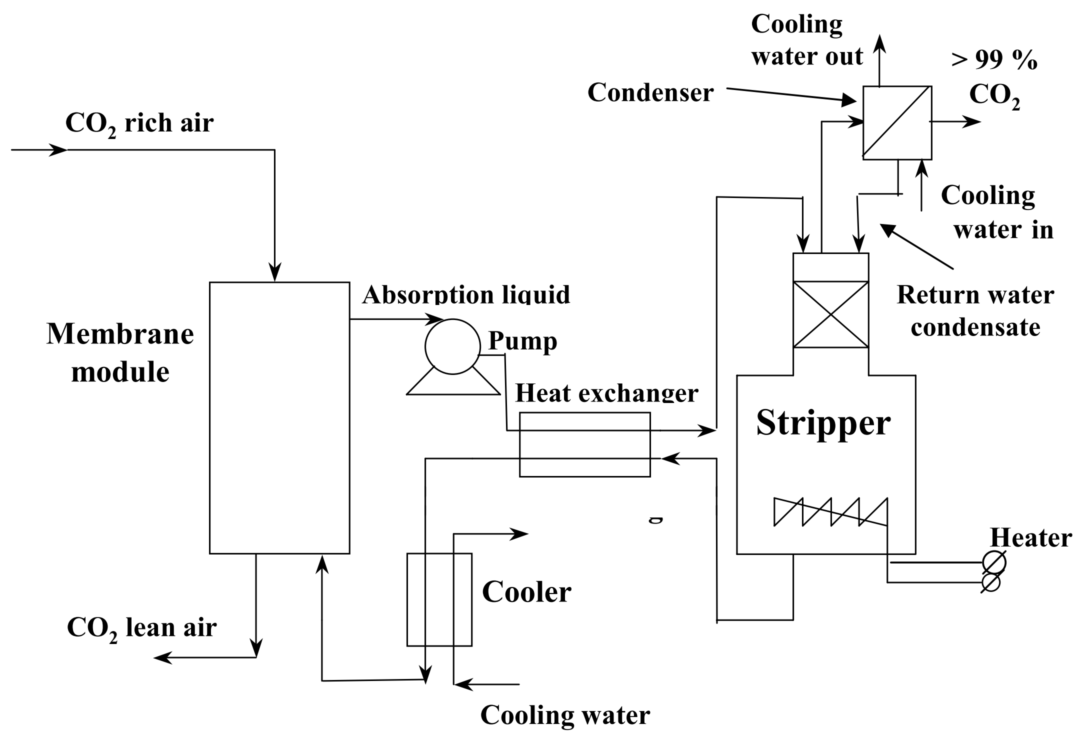

Figure 1: Membrane Gas Absorption (MGA) System

In 1995 the RNLN started a cooperation program with TNO to, firstly, provide a proof of principle of a new and promising technique for CO_2 removal, and, depending on the results, to subsequently define a development program for a system for CO2 removal on board HNLMS submarines. The proof of principle was successful and was followed by a proof of concept in 1999. Present development work is aimed at the realization of a full-sized demonstrator.

Besides the promised benefit of operating at low CO_2 concentration levels, the other main benefit of the MGA technique is that it is regenerative. It may operate continuously and the operational and logistical support will be significantly less compared to the current system based on the replacement of sodalime canisters. In the gas absorption process, a membrane separates the working fluid from the submarine atmosphere. CO_2 passes through the membrane into the absorption fluid. The fluid is regenerated at elevated temperatures.

System Description

Figure 1 describes the MGA system. CO_2 rich air passes through the membrane module, in which a hydrophobic membrane separates the working fluid and air (figure 2). The porous nature of the membrane allows a transfer of CO_2 to a working fluid of patented composition. The fluid is subsequently pumped through a heat exchanger for preheating after which it enters a so called "stripper" module and is heated further. CO_2 together with water is boiled out and leaves the stripper module. Water is separated from the CO_2 gas stream in a condenser and flows back to the stripper. After leaving the stripper the working fluid passes through the above mentioned heat exchanger and is subsequently cooled before it returns to the membrane module. The gas stream of more than 99 % pure CO_2 is compressed and ejected in the sea water.

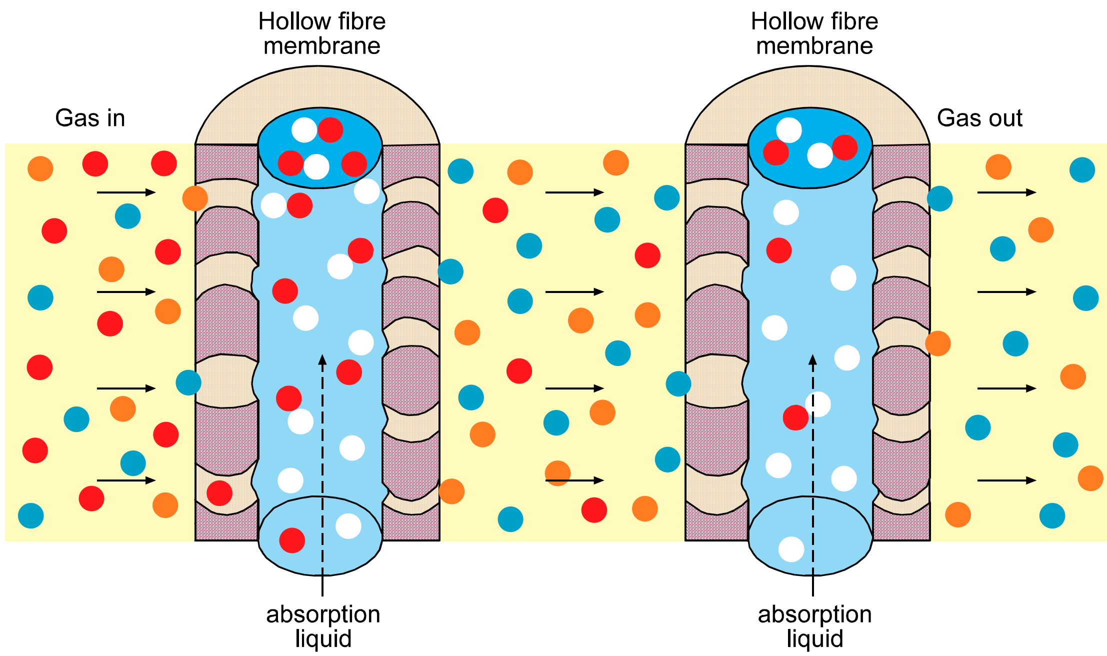

Figure 2: Hydrophobic membrane separates the working fluid and air

Development work is based on patents US 5,230,796 of 27 July 1993 [1] and US 5,749,941 of 12 May 1998 [2], which describe the membrane module and the characteristics of the absorption liquid respectively. The direction of the ambient gas flow is along the module perpendicular to, and across the module, the same, across or against that of the working fluid.

The second patent describes the composition of absorption fluids which are best suited to remove gaseous components from a gas stream by means of polyolefin membranes. Moreover, these fluids show no leakage across the membrane, little vapour losses, and are less corrosive and more oxygen resistant than other currently used fluids, e.g. monoethanolamine. Previous experiments have shown that the absorption fluids are regenerative and do not deteriorate during thermal cycling or exposure to ambient air. Ambient oxygen and nitrogen losses are negligible.

Previous Paper and Development Work

This paper is an update of a paper presented at the SAMAP 2003 conference [3] and describes the system development since then by both TNO and the NL MOD. The previous paper dealt with the subsequent project phases (proof of principle, proof of concept) and development work up to 2003.

The proof of principle phase (1995) included laboratory experiments at two distinct CO_2 concentration levels (0.5 % and 1.5 %) and a process evaluation which resulted in a preliminary design able to remove 2.5 kg/h of CO_2, equivalent to the production of 55 persons. The experimental set-up was not to scale. Aim during the next phase, the proof of concept phase (1999), was to provide a detail design of a CO_2 MGA system for HNLMS submarines. The result was a base line design which preceded a detail design study. The proof of concept phase further included a review of conditions for the application of a MGA system and laboratory experiments of a system with similar performance as the one intended for submarine deployment.

The requirement for the proof of concept phase was a minimum CO_2 removal capacity of 2.5 kg/h, equivalent to the production of 55 persons. The aim was to keep the CO_2 concentration level between 0.5 and 1.0 %. The electrical energy consumption is intended to be lower than 5 kW including that of the CO_2 compressor, and during stand-by mode lower than 0.5 kW. The system should comply with specific submarine environmental conditions and requirements, e.g. variations in temperature, relative humidity and ambient pressure, ship's motion, shock, vibration, noise, air quality, EMC and (fire) safety.

Experimental validation during the proof of concept phase was aimed at providing insight into a full scale system – contrary to the proof of principle phase –its energy consumption, performance of the membrane absorber and thermal regeneration process, and the sizing of plant equipment. A further aim was (and still is) to reduce the size of the final system. The experiments have shown that the ambient CO_2 concentration level largely determines the resulting CO_2 flow rate across the membrane. Higher levels result in a higher CO_2 flow rate. A specific heat consumption of 5 MJ/kg of CO_2 for the process was shown possible. The predicted maximum electrical energy consumption is below 3.7 kW and includes consumption of ventilator, heating element, compressor and pump.

Discussion with the intended manufacturing subcontractor resulted in a detail design which assumed the installation of two systems each capable of removing 2.5 kg/h of CO_2 during normal operation. Characteristics of the detail design are as follows (excluding compressor):

Component	Type	Capacity
Membrane absorber	DAM-Q3/2	80 m^2
Ventilator	Centrifugal	550 m^3/h
Pump	Gear	120 l/h
Heat exchanger	Plate	12.6 kW
Cooler	Plate	0.65 kW
Stripper including storage	Tube	0.25 m diameter × 1.1 m
Condensor	Pipe	1.8 kW
Heating element	Electrical	4.0 kW

Development Work Since 2002 (Realization of a Full-Sized Demonstrator)

In July 2002 the RNLN has asked TNO to start the present development program aimed at the realization of a full-sized demonstrator for operation on board one of HNLMS submarines, able to remove 2.82 kg/h of CO_2, equivalent to the production of 62 persons. This number represents the maximum number of crew and sea riders on board. The number of 55 persons in the previous project phases represents the maximum number of crew excluding sea riders. However, most of time the submarine sails with 62 persons for training and operational purposes. The program deliveries further include laboratory performance tests, shock tests and plans for on board installation, maintenance, training and sea trials.

The plan was to finish the program by the end of 2003 and start the engineering for installation on board. However, discussions on the final specification of the demonstrator and change of the intended location on board have delayed the program execution. Further delays were a result of membrane testing which showed a gradual decrease of absorption capacity. The program is expected to conclude in 2006. Depending on scheduled submarine

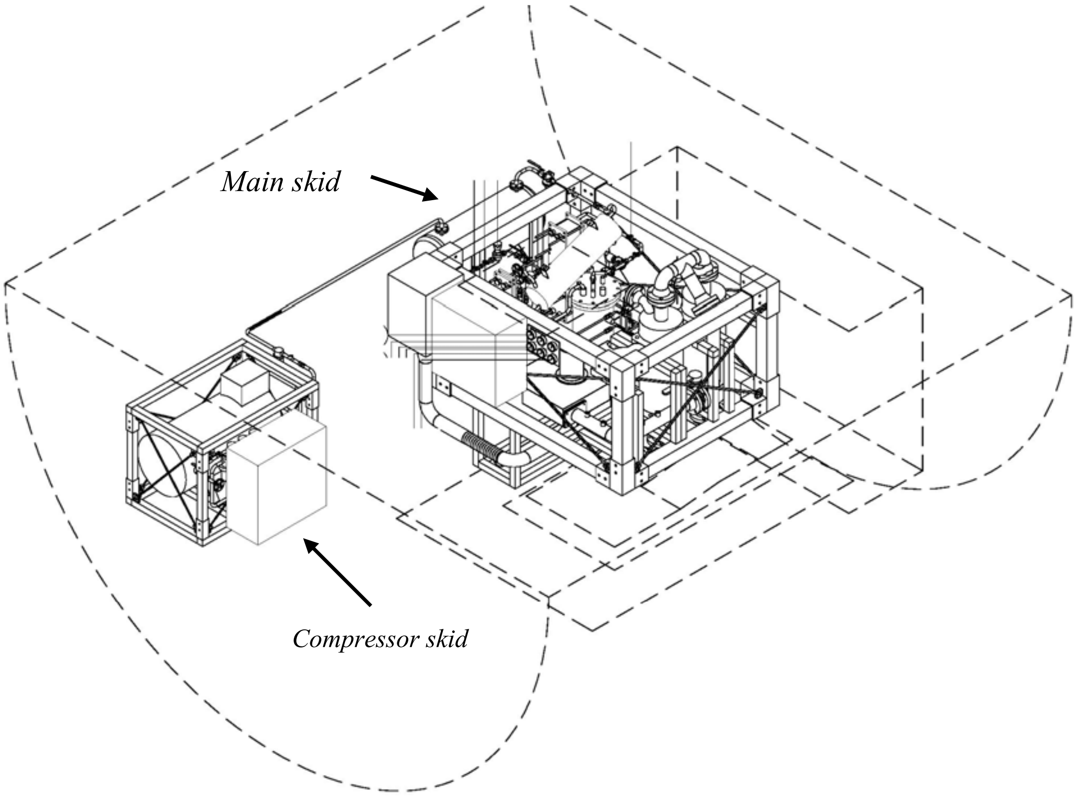

Figure 3: SE View of complete system (looking forward and to port)

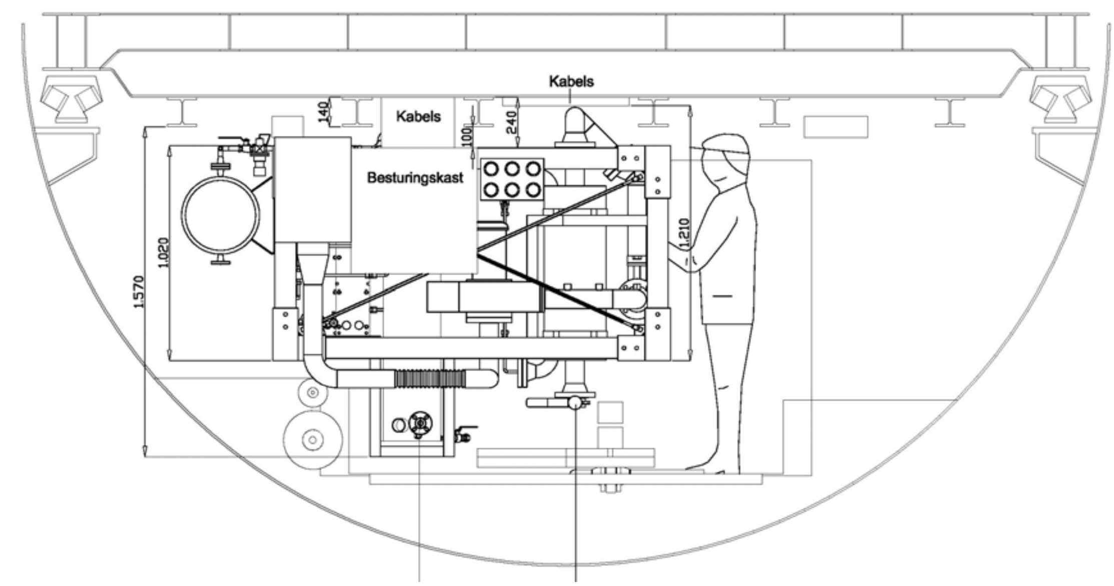

Figure 4: Side view of main skid (looking forward)

maintenance, installation on board is now foreseen by the end of 2008, with subsequent sea trials during 2009.

Figures 3, 4 and 5 show the latest design. Dimensions and a list of components are available. Figure 6 shows the recent test results of a MEMBRANA X40 membrane module. Figures 7 and 8 are pictures of the outside of the membrane module. Overall length of the module is 1.2 m and diameter is 30 cm. Housing material is stainless steel.

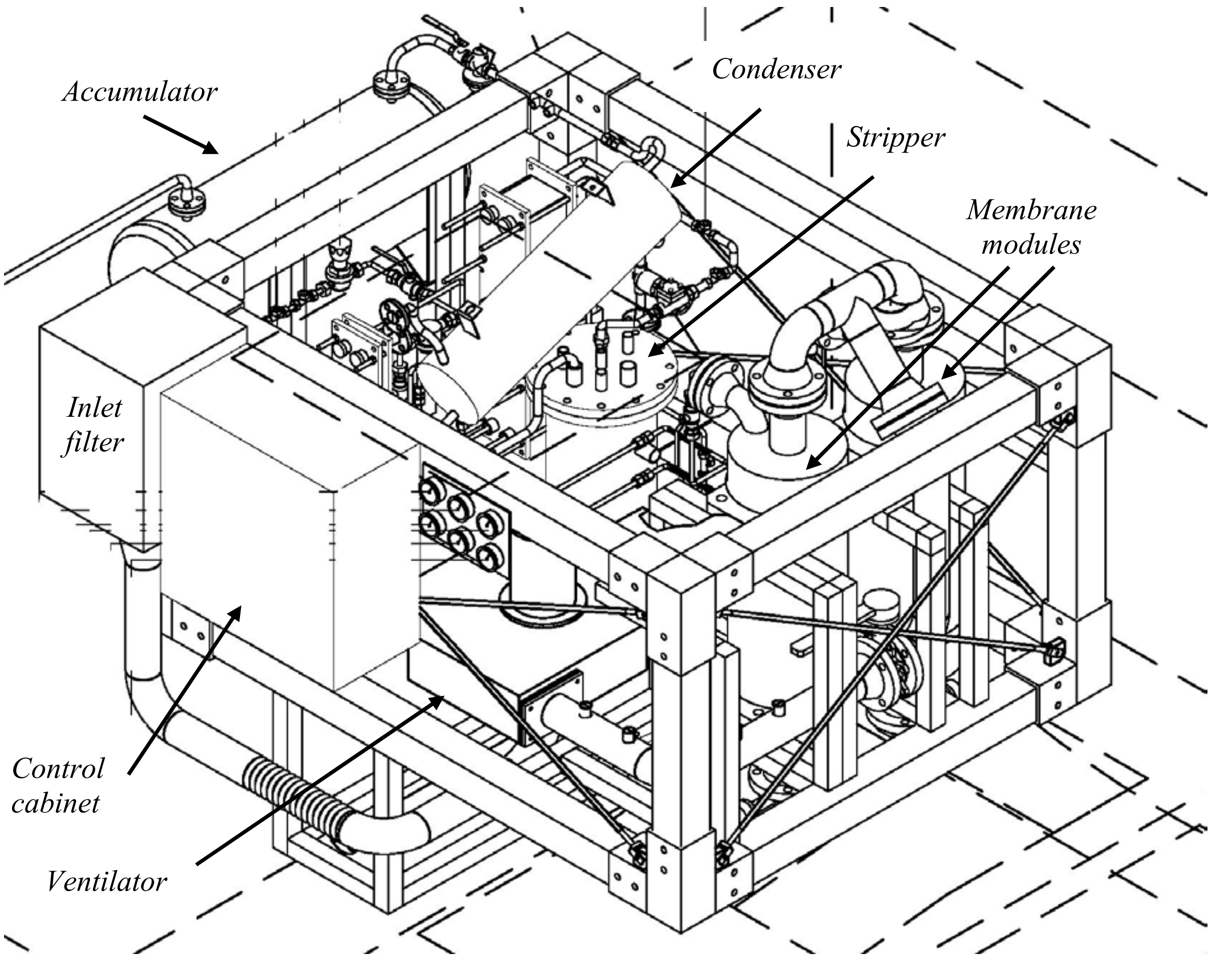

Figure 5: View of main system (looking forward and to port)

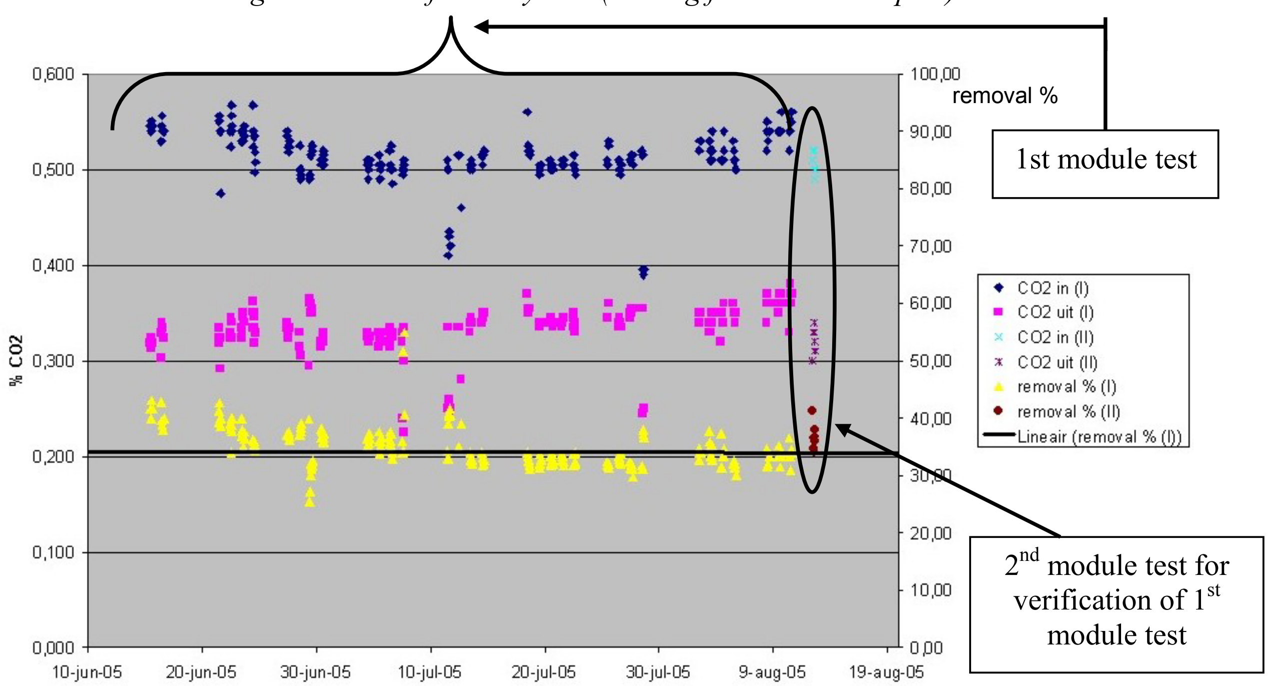

Figure 6: CO2 absorption test results X40 membrane module

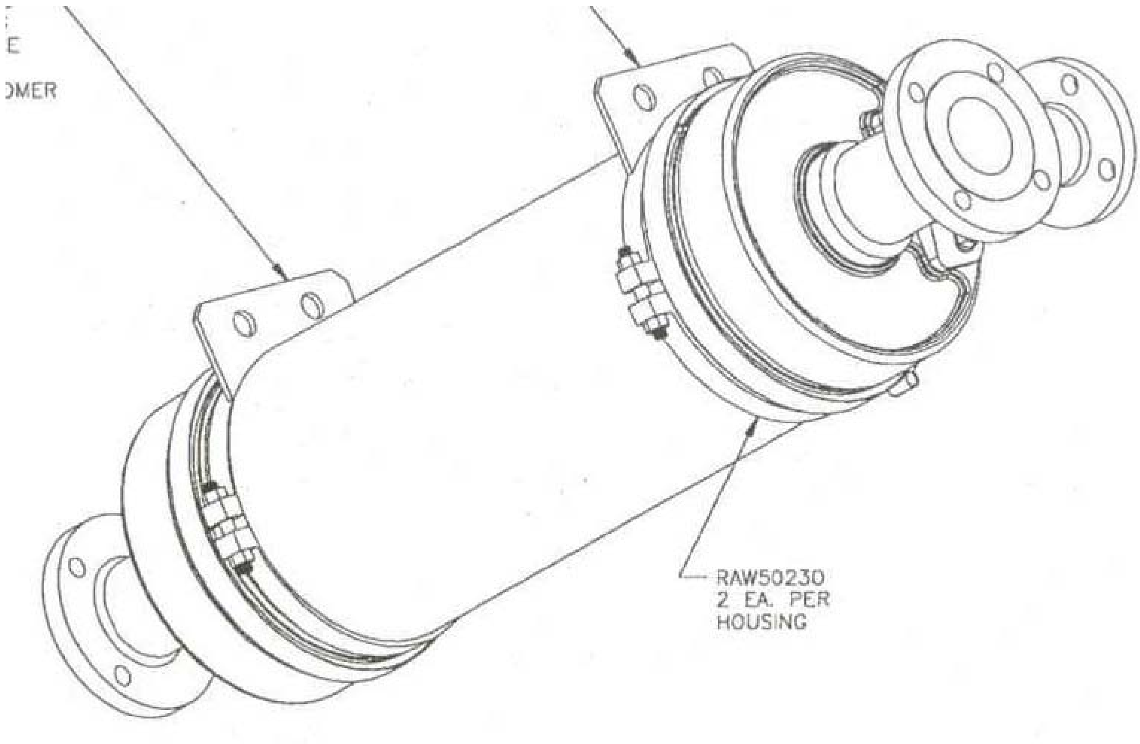

Figure 7: 3D view of X40 membrane module

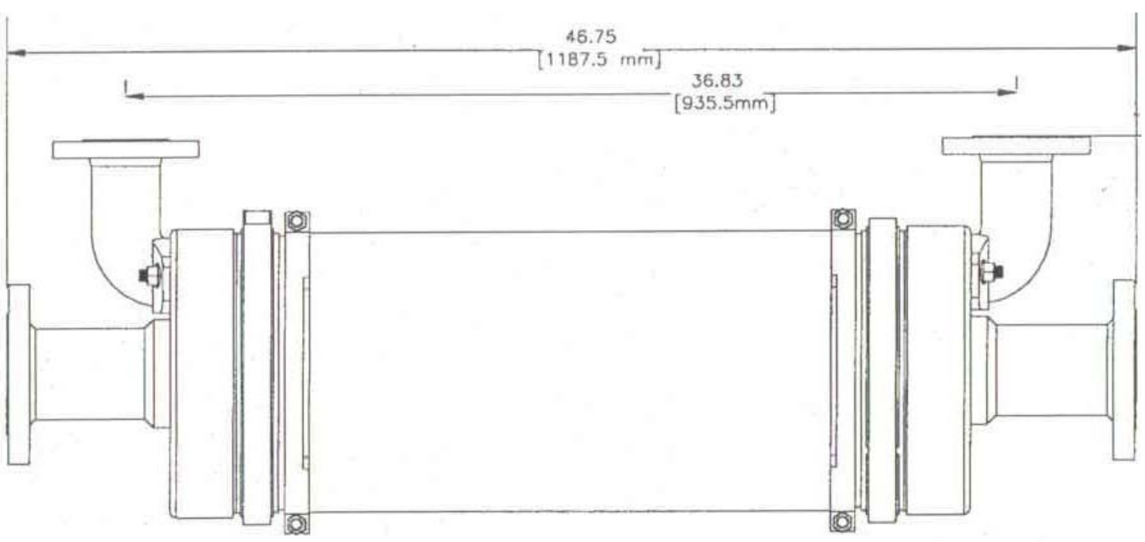

Figure 8: Side view of X40 membrane module

The test results (figure 6) show a stable absorption process. The inlet concentration level is approximately 0.5 %, the outlet concentration is approximately 0.35 %. Removal percentage is approximately 35 % (v/v). These results are an end result of tests that began in 2004. As previously indicated, early tests showed a decreasing absorption capacity with time. Initially TNO was suspected that the cause for this decrease may have been pollution of the membrane by ambient air. However, this appeared not to be the problem.

Later, the research was focused on the combination of the type of membrane and the concentration of the absorption liquid. The liquid is a salt solution. The solution appeared to crystallize at high concentration levels during standstill of the absorption liquid flow. In the beginning of this year (2005) TNO in discussion with the RNLN have decided to lower the concentration levels of the absorbing salts. Consequently the air flow across the membrane module had to be increased to compensate for the resulting decrease in absorption capacity. Furthermore, TNO have selected a membrane that is less porous and allows less evaporation across the membrane, i.e. the MEMBRANA X40 type membrane.

The result of the change in design is a membrane module that is able to absorb approximately 900 g of CO_2 per hour at 0.5 % input CO_2 concentration with a required air flow of approximate 270 m^3 per hour. Before the decision to lower the absorption liquid concentration level, 2 membrane modules would have satisfied the required 2,82 kg/h of CO_2 absorption from the atmosphere at 0.5 % input CO_2 concentration, equivalent to the production of 62 persons. After the change in design the system would, without compromise to the CO_2 input concentration, as a minimum include 3 membrane modules (2.7 kg/h @ 0.5 % CO_2 in, sufficient for 59 persons at 810 m^3/h of ventilation) and maximum 4 (3.6 kg/h @ 0.5 % CO_2 in for 79 persons at 1080 m^3/h of ventilation). The system in figure 5 has space available for 3 modules. A system with 4 modules will be larger. A system with 3 modules would be able to absorb 2,82 kg/h of CO_2 but at a higher CO_2 input concentration level (TBD).

The plan is to assemble a complete system by the end of 2005 followed by performance tests at different ambient conditions at the beginning of 2006. Test results of the complete system together with submarine availability during planned maintenance will determine the period of installation on board. Operation on board an operational submarine is foreseen by 2009.

The Naval Dock Yard at Den Helder will be responsible for installation of the system on board. Design issues are the interfacing with the existing submarine structure and systems. In particular the size of the system will make installation, accessibility and future maintenance difficult. The Naval Dock Yard has further developed an experimental set-up to inject CO_2 into sea water. The plan is to first inject CO_2 into a pressurized water tank as a quasi-static condition and later install the set-up on board for dynamic trials.

Conclusion

The presented system promises to achieve lower CO_2 concentration levels (between 0.5 and 1.0 %) and is regenerative. The operational and logistical support will be significantly less and the system may operate continuously. However, energy consumption will be an order of magnitude higher than that of the present system which uses Sodalime canisters.

References

[1] *Transfer Device for the Transfer of Matter and/or Heat from one Medium Flow to another Medium Flow*, United States Patent, Patent Number 5,230,796, Date of Patent 27 July 1993.

[2] *Method for Gas Absorption across a Membrane*, United States Patent, Patent Number 5,749,941, Date of Patent 12 May 1998.
[3] *Future CO_2 control using membrane gas absorption on board HNLMS submarines*, paper presented at SAMAP 2003 conference, Emden, Germany, authors Martin Jansen (NL MOD) and Paul Feron (TNO-MEP), October 2003.