DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

INTRODUCTION

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1.
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DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

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The idea to use dissolved oxygen (DO) for AIP submarines is not new. Nevertheless, there is common opinion that it is **impossible** using dissolved in seawater oxygen to provide operation of submarines' AIP systems.

We had implemented analysis of different configurations of AIP and dissolved oxygen extraction systems (DOES) and had found that, there are such configurations of DOES that can be used in submarines instead of LOX systems. At least, the calculation results of these configurations of DOES gave optimistic evaluation.

Using DOES instead of LOX system promises serious advantages for AIP submarines.

The main goal of this publication is to show that dissolved oxygen (DO) extracted from seawater can be used as a real source of oxygen for submarine's AIP systems. In particular, the feasibility analysis shows that suggested technical solutions enable to provide the submerged operation of 300kW fuel cell AIP system.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
INTRODUCTION

In the one of a next chapters we shall give substantiation of the initial data that were used in conceptual calculations of DOES.

To realize DOES conceptual solution, we shall have to perform examinations of some interim technical solutions that are important to reach general goal of the project.

In the one of a next chapters we shall give preliminary list of technical problems that have to be solved to reach general goal of the project.

Obviously, that sea trial results only will be able to demonstrate feasibility of the technical proposal.

The publication is intended for investors that are interested in submarine AIP systems development and are ready to invest detailed design, manufacturing and sea trials of systems for DO extraction from seawater.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING LIQUID OXYGEN STORAGE SYSTEMS DRAWBACKS

All modern AIP submarines use liquid oxygen (LOX) to provide operation of an AIP system.

There are four main types of AIP systems. Every type of the system is based on:

- Fuel cell (German – Submarines: Type 212/212A; Type 214);

- Closed cycle Stirling engine (Sweden – Submarines: Gotland, A26 class; Japan boat Soryu class);

- Closed cycle steam turbine MESMA (France – Submarines: Agosta 90B, Scorpene AM2000 class; India – Kalvary S50 class);

- Closed cycle diesel engine (Dutch – Submarines: Moray 1400H and 1800H class).

Every AIP type contains its LOX storage system.

Any LOX storage system includes a LOX tank (or tanks); LOX fuelling, LOX feeding and other auxiliary systems.

Usually, oxygen is delivered by a road tanker in special fitted ports. The time of filling is only dependent on the amount of oxygen loaded. Depending on the length of the mission, LOX can be loaded into either, or both tanks.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

EXISTING LIQUID OXYGEN STORAGE SYSTEMS DRAWBACKS

Table. LOX Storage Systems Drawbacks

Items	LOX Storage Systems Drawbacks
1	Amount of LOX on sub board defines submerged endurance of submarine.
2	LOX tanks have large dimensions and weight.
3	AIP submarine can be charged by LOX in special ports or by a road tanker. These ports has to be fitted with LOX storage and special cryogenic fueling system. In all cases, submarines have to be surfaced to be charged.
4	LOX is the dangerous cryogenic liquid (boiling point is −182.96°C at 1.0 atm).
5	LOX is in tanks under high pressure from 20 to 60 bars (MESMA).
6	LOX tanks have to be super-insulated and have anti-splash and shock-proof complicated structure.
7	LOX consumption demands of longitudinal balancing of a submarine.
8	Relatively short life time of oxygen storage as result of oxygen losses.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
ADVANTAGES OF USING DISSOLVED OXYGEN IN SUBMARINE

Table. Advantages of Using Dissolved Oxygen in Submarine

Items	Advantages of Using Dissolved Oxygen in Submarine
1	**Amount of oxygen does not limit submerged endurance of submarine. Until fuel exists a DOES can extract dissolved oxygen (DO) from seawater.**
2	**DOES is relatively compact and have relatively low weight.**
3	**AIP submarine can extract oxygen in any place of Global Ocean.**
4	**Oxygen is extracted from seawater in gaseous form and can be used at once by AIP converter.**
5	**DOES can provide oxygen pressure from 1.0 to 10.0 bars**
6	**Besides oxygen a DOES extracts nitrogen, argon and carbon dioxide from seawater. The mixture of extracted gases enriched by oxygen can be used for exchange atmosphere inside submarine.**

1.1.
LOX STORAGE SYSTEMS
ONBOARD EXISTING AIP SUBMARINES

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

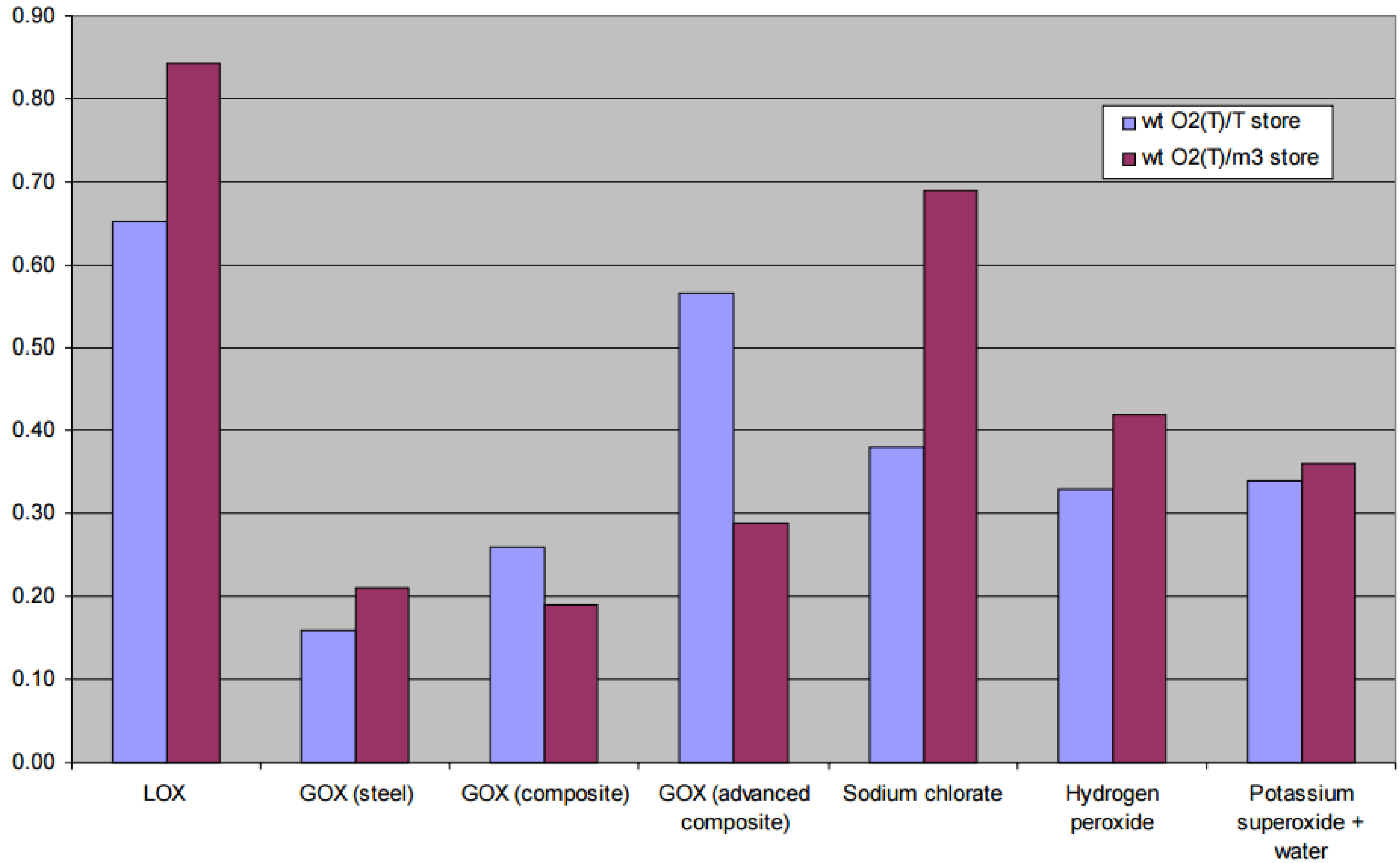
LOX STORAGE SYSTEMS ONBOARD EXISTING AIP SUBMARINES

There are some oxygen storage/production conceptual solutions that are applied in submarines, aircrafts, and laboratory technique.

Items	Oxygen Storage System	Method of Gaseous Oxygen Production	Applications
1	Storage of Oxygen as a Cryogenic Liquid.	Evaporation of LOX	Submarines
2	Storage of Oxygen as a Compressed Gas.		Laboratory technique
3	Storage of Oxygen as a Chemical Composition. Sodium chlorate ($NaClO_3$). Potassium chlorate ($KClO_3$).	Heat Decomposition with or without of catalyst (MnO_2)	Aircrafts, Laboratory technique
4	Storage of Oxygen as High Test Peroxide (H_2O_2).	High temperature Decomposition	Submarines

All these methods had been compared each to other. Comparison results are given in the next slide. <u>Storage of Oxygen as a Cryogenic Liquid has advantages</u>. Ratio of stored LOX mass to mass of full LOX tank is Km= 0.65max., (Km=0.25 – 0.5 for submarine LOX tanks)

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
Comparison of Different Technologies for Oxygen Storage

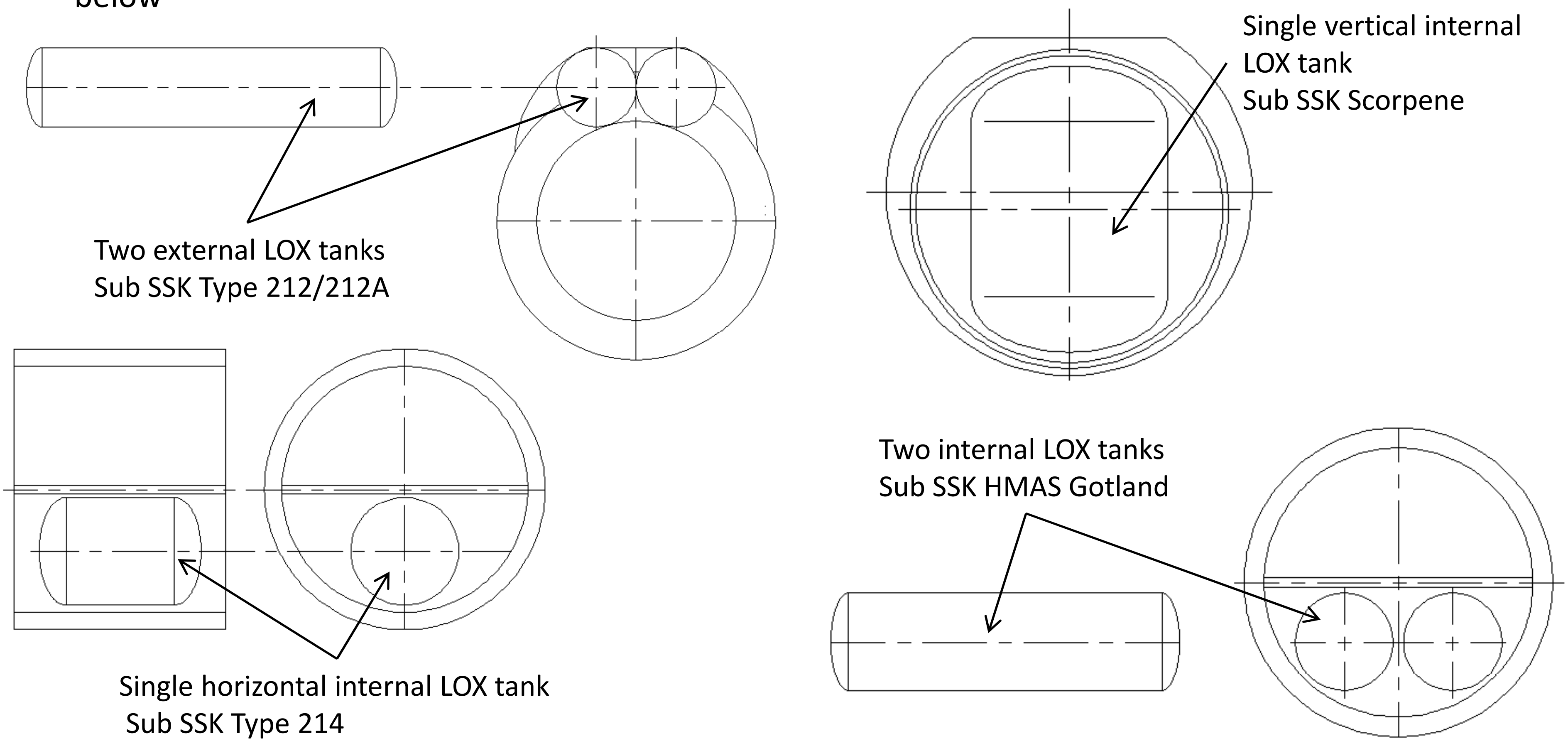


Lakeman J. B., Browning D. J., The Role of Fuel Cells in the Supply of Silent Power for Operations in Littoral Waters. NATO RTO-MP-104, 00 APR 2004 http://www.dtic.mil/dtic/tr/fulltext/u2/a428713.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

LOX STORAGE SYSTEMS ONBOARD EXISTING AIP SUBMARINES

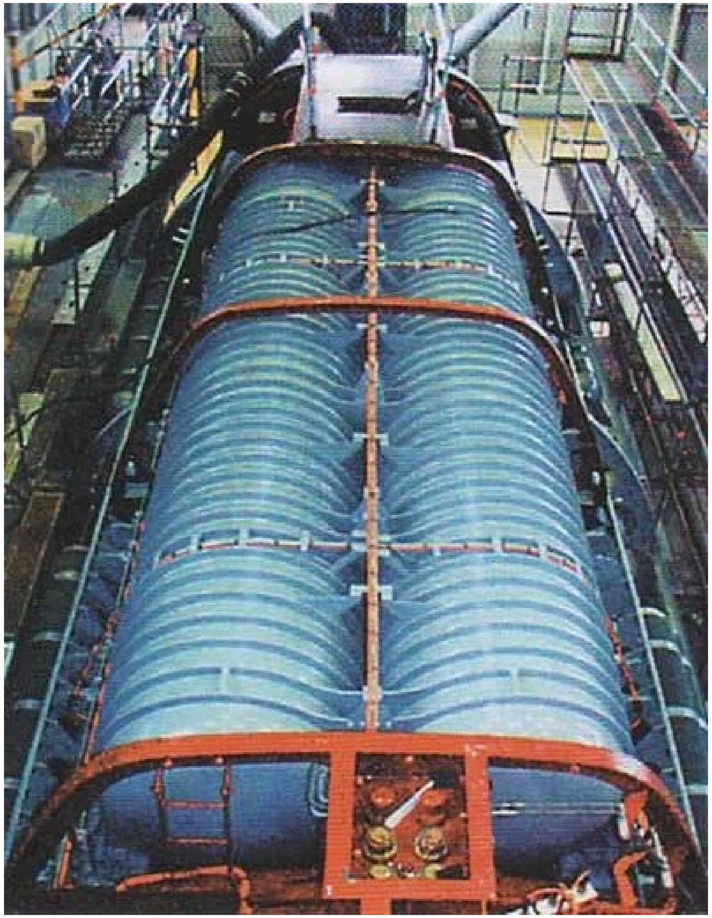
There are some configurations of LOX storage systems for existing AIP submarines. Every configuration have both advantages and drawbacks. The schematics of these configurations are given below



DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

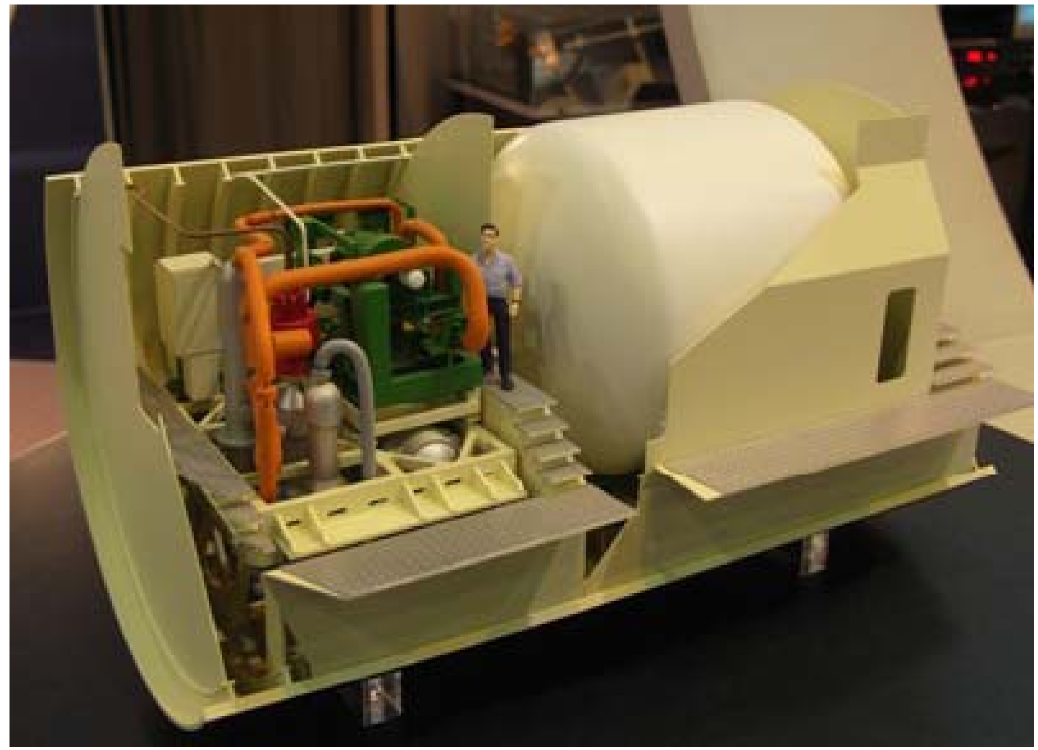
LOX STORAGE SYSTEMS ONBOARD EXISTING AIP SUBMARINES

LOX tank for German
SSK submarines Type 212/212A



LOX tank for German SSK submarines Type 214

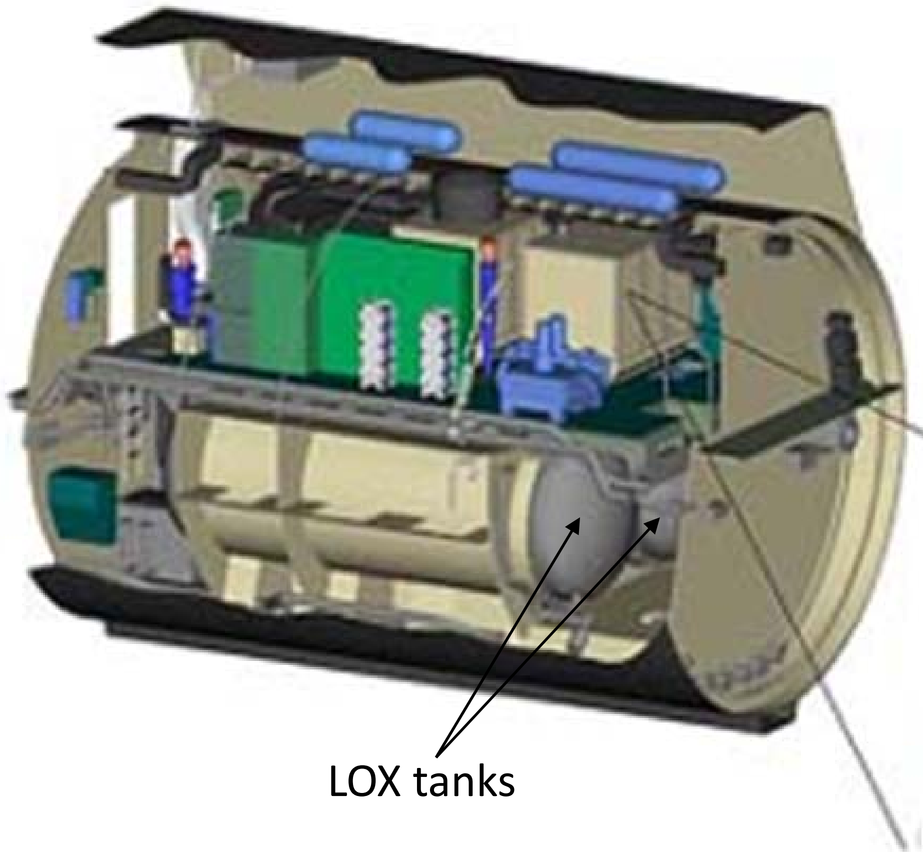
DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
LOX STORAGE SYSTEMS ONBOARD EXISTING AIP SUBMARINES



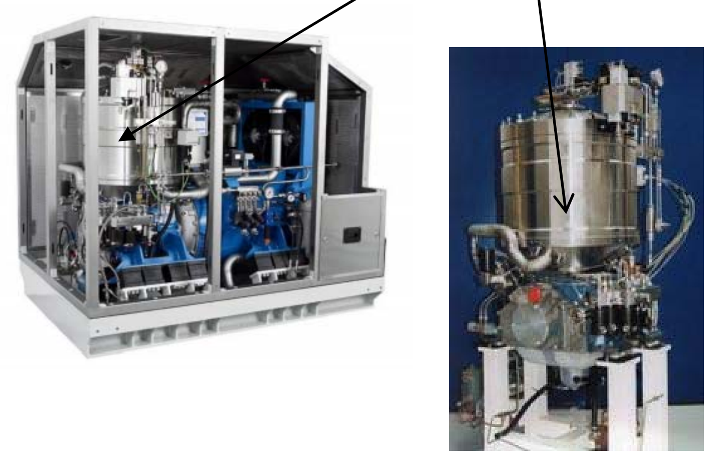
AIP “MESMA” with Vertical and Horizontal options of LOX Tank.

French SSK submarines SCORPENE and AGOSTA-90B are fitted with AIP “MESMA”

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
KOCKUMS AIP Stirling Section



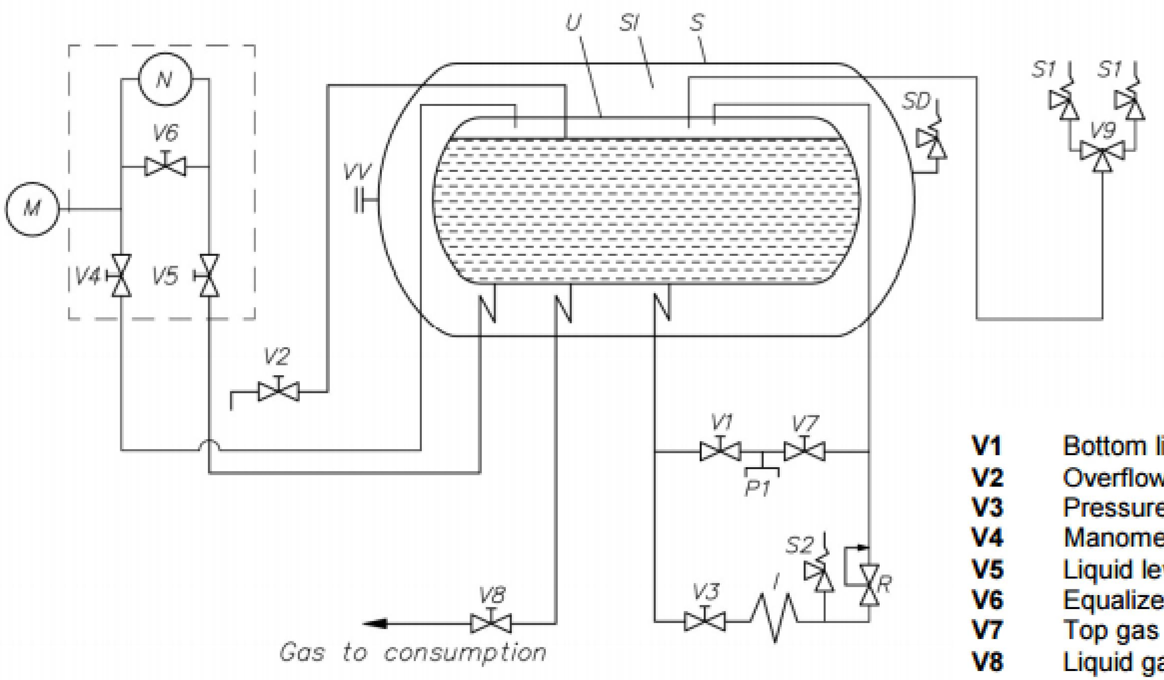
KOCKUMS Submarine Systems Corp., is the builder of Swedish AIP submarines.
All AIP systems based on Stirling engine cycle and is placed in 8.5 m AIP section.
On the submarines HMAS SSK Gotland oxygen is stored cryogenically in two tanks located below the engine deck.



Usually, LOX tanks are designed for shock resistance and to minimize thermal losses. Analyses, performed to determine which tank shape would provide minimum losses, showed that two smaller tanks would be better than one large tank.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

HORIZONTAL LOX TANK STRUCTURE. FLOW DIAGRAM



Flow Diagram

V1	Bottom liquid inlet/outlet
V2	Overflow
V3	Pressure build-up
V4	Manometer valve/Liquid level(-)
V5	Liquid level (+)
V6	Equalizer valve
V7	Top gas inlet
V8	Liquid gas to product vaporizer
V9	Three way valve / Diverter valve
U	Inner vessel
S	Outer jacket

SI	Multilayer insulation
S1,S2	Safety valve
SD	Safety disc
VV	Vacuum valve
I	Auxiliary vaporizer
I1	Product vaporizer
M	Manometer
N	Liquid level indicator
R	Pressure regulator
P1	Filling connection

http://kryooprema.com/hdiagram.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
Cryogenic LIQUID OXYGEN (LOX) Storage
LOX Tanks Calculation

Storage of Oxygen as Cryogenic Liquid

A certain commercial 29.6 ton tank has length 7400 mm and outer diameter 2600 mm (external volume 39.2 m3). Tare weight 13.5 ton and holds 18500 liters of LOX whose density at 20 bar(a) will be about ~0.87 gram/cm3. In this case the tank holds 18500*0.87=16095 ton of oxygen.

The storage factors (mass and volumetric) are:

SFm=29.6/18.5*0.87=1.84kg(tank)/kg(O2)

SFv=39.2/18.5*0.87=2.43liter(tank)/kg(O2)

For 1 Kg of oxygen you need either 1.82 kg of tankage or 2.43 liters.

In fact for a military purpose the tank has to contain a bit more than this.

For 1 Kg of oxygen it is required 2.0 kg of tank-mass or 2.8 liters of volume.

http://hydrogen-peroxide.us/uses-oxygen-generation/Morley-Air-Independent-Propulsion-Ch7-Sources-of-Oxygen-2005.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
Submarine LOX Tanks

This is not a particularly good example. We are aiming to have about 50 % of the full weight as being liquid oxygen.

Storage tank supplied by British Oxygen Ltd. Morley gives the following dimensions for a larger tank than might appear in a submarine.

LOX Tank Characteristics	Characteristics Value
Length with all fittings	7.4 m
Outside diameter	2.6 m
Volume of LOX tank	39.2 m3
Volume of LOX	18.5 m3
LOX pressure	20 bar(a)
LOX density	0.87 kg/m3
Tare density	0.65 kg/m3
Weight full	29.6 ton
Weight empty	13.5 ton

http://hydrogen-peroxide.us/uses-oxygen-generation/Morley-Air-Independent-Propulsion-Ch7-Sources-of-Oxygen-2005.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

LOX STORAGE SYSTEMs PERFORMANCE OF EXISTING AIP SUBMARINES

Table. Existing Submarines LOX Storage Systems Performance

Items	LOX Storage system data	Units	AIP PEMFC Type212	AIP PEMFC Type214	AIP Stirling	AIP MESMA
1	Submarine submerged displacement	ton	1830	1860	1599	1870
2	AIP power	kW	306	240	2x65	200
3	LOX specific consumption	Kg/kWh	0.4	0.4	0.95	1.14
4	LOX pressure	Bar(a)	2.5	2.5	5.4	60
5	LOX density	kg/m3	1086	1086	1030	1018.6
6	LOX tank number	-	2	1	2	1
7	Volume of inner LOX tank (approximate value)	m3	2x17.157	19.74	2x12.02	28.27
8	Outer volume of tank (approximate value)	m3	2x27.227	28.634	2x17.86	37.53
9	LOX weight (at filling factor fk=0.95) (approximate value)	ton	35.4	20.4	23.5	27.4

1.2.
USING DISSOLVED OXYGEN IN SUBMARINE'S AIP SYSTEM.
IS IT MYTH OR FEASIBLE PROBLEM?

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

OXYGEN FROM SEA WATER

DC W. Morley Air Independent Propulsion CHAPTER 7 - SOURCES OF OXYGEN IN A SUBMARINE. Nov., 2005 [7]

http://hydrogen-peroxide.us/uses-oxygen-generation/Morley-Air-Independent-Propulsion-Ch7-Sources-of-Oxygen-2005.pdf

In addition to the various oxygen production concepts, "there is the question that never seems to go away **"Can you get oxygen out of the sea water?"** Leaving aside the weak minded brethren who think you might be able to decompose the water somehow, there is the question of the oxygen dissolved in the sea water or otherwise held there. Now, the short answer to the question is **"No, because there is not enough dissolved oxygen"**. This can be illustrated very well by the case of the Closed Cycle Diesel which not only breathes oxygen, but has water brought to it to dissolve away the waste carbon dioxide.. The diesel needs about 1.50 moles of oxygen per second. 50 liters/sec of water are brought to the engine (to dissolve the CO2) and they bring with them about 0.016 moles of oxygen/sec.

Notwithstanding this typical arithmetic, there have been a number of proposals in recent years for artificial gills. The ones I have seen have all had the same error in the calculations : They have neglected to add in the power needed to pump the (vast amount) of water past the gills. The power needed is far more than could be supplied by an engine using all the oxygen that the gill supplied. Nevertheless, every few years there is a paper on the idea. Use it for an exercise in arithmetical assassination"

http://hydrogen-peroxide.us/uses-oxygen-generation/Morley-Air-Independent-Propulsion-Ch7-Sources-of-Oxygen-2005.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

OXYGEN – GENERATION ONBOARD

Grant B. Thornton, A DESIGN TOOL FOR THE EVALUATION OF ATMOSPHERE INDEPENDENT PROPULSION IN SUBMARINES. Thesis., Massachusetts Institute of Technology, 1994-05. [8]
http://calhoun.nps.edu/handle/10945/42961

“One other onboard generation option is the extraction of oxygen for the ocean itself. Artificial gill technology involves the use of a porous membrane which only passes gas molecules to extract the dissolved oxygen from the sea. Oceans in the northern latitudes possess the required oxygen concentration, greater than 4 ml/l of seawater, necessary for this technology to be successful. The present state of development for this technology renders it as large and bulky, requiring approximately 30 percent of the electricity that its oxygen can produce. Further development may make this technology a viable option for the future”.

Grant B. Thornton, A DESIGN TOOL FOR THE EVALUATION OF ATMOSPHERE INDEPENDENT PROPULSION IN SUBMARINES

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

SEPARATION OF OXYGEN FROM SEAWATER

Bell, C.M. Chow P. and Baker R.W. SEPARATION OF OXYGEN FROM SEAWATER BY MEMBRANE PERMEATION March 1989 Final Technical Report for period 31 August - 28 February 1989 [9]

http://www.dtic.mil/dtic/tr/fulltext/u2/a208863.pdf

"A reliable method for extracting oxygen from Seawater it required for a number or naval applications. This program describe: the development of a membrane system to perform this extraction. Seawater containing dissolved air is brought in contact with a suitable membrane, and the dissolved air preferentially permeates the membrane. In this Phase I program two thin-film composite membranes were evaluated and the feasibility of the approach was demonstrated using a small bench-scale system fitted with a 6-m2 spiral-wound membrane module. Approximately 40% of the dissolved oxygen in seawater could be removed in a single pass through the membrane module.

The oxygen concentration of the permeate gas was 33%.

A technical analysis was conducted for the application of this technology for life support an submarines, and (2) oxygen supply for submerged fuel cells. The analysis showed the fuel cell application to be the most promising. In this application the power consumption of the oxygen extraction process is 25% of the energy produced by the fuel cell.".

http://www.dtic.mil/dtic/tr/fulltext/u2/a208863.pdf

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

Dissolved Oxygen (DO) Production from Seawater. Methods

ARTIFICIAL GILLS. https://en.wikipedia.org/wiki/Artificial_gills_(human)

"Several potential methods exist for the development of artificial gills. One proposed method is the use of liquid breathing with a membrane oxygenator to solve the problem of carbon dioxide retention, the major limiting factor in liquid breathing.

It is thought that a system such as this would allow for diving without risk of decompression sickness.

They are generally thought to be unwieldy and bulky, because of the massive amount of water that would have to be processed to extract enough oxygen to supply an active diver, as an alternative to a scuba set.

An average diver with a fully closed-circuit re-breather needs 1.5 liters per minute while swimming or .64 liters of oxygen per minute while resting. As a result, at least 192 liters (51 US gallons) of sea water per minute would have to be passed through the system, and this system would not work in anoxic water. Seawater in tropical regions with abundant plant life contains 5-8mg of oxygen per liter of water. These calculations are based on the dissolved oxygen content of water".

https://en.wikipedia.org/wiki/Artificial_gills_(human)

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

Sea is a Huge Container to Storage Dissolved Oxygen.

Atmospheric air contacting with seawater is solved in water partially. Essentially, it is concerned of all gases is being contained in air. Theoretically solubility of gases in water is based on Henry law.

It is known that the main gases dissolved in seawater are: oxygen (O2), nitrogen (N2), argon (Ar) and carbon dioxide (CO2). These gases have maximal partial pressures and relatively low values of Henry coefficient (K_H). It provides relatively high penetration, diffusivity and solubility of these gases in seawater.

The oxygen solubility in seawater essentially depends on following seawater characteristics: temperature, depth and salinity.

The content of oxygen is considered against to Ocean's latitudes, littoral waters and open sea, seasons, and time of day. In this connection, it is evaluated the minimal, average and maximal concentrations of oxygen in littoral waters at the typical depth of submarine patrol operations.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER
EXISTING VIEWS ON TECHNICAL FEASIBILITY TO USE DO IN AIP

There are some degassing technologies that can be selected to provide extracting oxygen from seawater. Selection of the technology to extract oxygen from seawater will be described in the one of the next chapters.

The feasibility analysis includes some following steps:

- Estimation of oxygen productivity from seawater;
- Required power to provide given consumption of oxygen;
- Approximate evaluation of dimensions and weight of AIP system.

There are some different schematics of AIP system that have to be examined during tests to define the optimal AIP design. Especially, it should be noted that proposed AIP system has no principal differences from existing AIP systems.

The publication is intended for investors that are interested in submarine AIP systems development and are ready to invest detailed design, manufacturing and sea trials of systems for DO extraction from seawater.

DISSOLVED OXYGEN EXTRACTION FROM SEAWATER

CONCEPTUAL DESIGN STEPS OF PLANT FOR DO EXTRACTION FROM SEAWATER

Conceptual Design Steps:

1. Define oxygen mass flow rate required for AIP operation;
2. Evaluation of dissolved oxygen concentration in seawater;
3. Define DOES specifications (list of requirements):
4. Dissolved oxygen extraction system selection;
5. Evaluation of installed power capacity of DO extraction system;
6. Evaluation of DOES weight and dimensions.

1.3.
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Thanks for your attention