AIR PURIFICATION IN CONVENTIONAL SUBMARINES

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ABSTRACT

The article starts by giving an introduction into submarine air purification in general. Consideration is then given to the selection of various air purification systems for conventional submarines and the possible benefits and drawbacks that each would bring. Finally a brief summary of current R.N. developments is made.

Introduction

The subject of submarine air purification is complex and extensive. In one way or another it effects the design of all areas of the vessel. As the dived endurance of conventional submarines continues to improve, the revitalization of the air becomes increasingly more involved and important. This article investigates the problems and speculates upon a number of solutions.

History of Air Purification in R.N. Submarines

Earlier submarines followed the practice adopted in the HOLLAND Class, the first truly modern submarines of about 1900, in making little effort to control the atmosphere. Due to their very limited battery capacity, they were only capable of relatively short dives before they had to surface and recharge. This routine ensured that the air within the submarine was frequently changed and remained capable of supporting life. It was only as submarines became capable of much longer dives that air purification became an issue. Initial studies concentrated on carbon dioxide removal, as it is the build-up of this gas which is the most limiting. However, as submarines became capable of diving for longer than twenty-four hours, oxygen replenishment became necessary as well. The recent adoption of air-independent propulsion systems by certain navies introduces much more complex problems.

The earliest record of air purification equipment being fitted to R.N. submarines can be found in the reports of a series of trials conducted in the Mediterranean aboard H.M.S. *Swordfish* in 1932. They involved the installation of soda lime trays in the ventilation system for the removal of carbon dioxide. Although successful in removing carbon dioxide, introduction into service was not recommended as it was considered that a greater limitation on the dived endurance was imposed by the capacity of the main battery. This conclusion was understandable when one looks at the very high permitted carbon dioxide limits of the time.

In 1939, following the loss of H.M.S. *Thetis*, Admiral Dunbar-Nasmith carried out an investigation[1] into methods of saving life in sunken submarines. He stated that it was vital to provide a means of keeping the air fresh before escape attempts were made and specifically recommended that this be done using individual respirators. Due to the outbreak of the second world war, this recommendation was not acted upon. However it was soon discovered that submarines operating close in to the hostile Norwegian shore in summer were vulnerable to air attack; carbon dioxide build-up prevented them remaining dived throughout the long arctic day. As a rush solution, certain submarines were equipped with carbon dioxide monitors and soda lime absorbers, despite the misgivings of Captain P. A. Ruck-Keene of the 3rd Submarine Flotilla, who wrote:

> Although such an instrument is desirable, an accurate knowledge of the amount of CO_2 present is a double-edged weapon and may possibly make the men think they are worse than they are really.

By 1946 these doubts had obviously faded as, by now promoted rear-admiral, he carried out a further review[2] of submarine escape procedures. His report strongly recommended the provision of improved atmosphere monitoring and air purification equipment independent of the main submarine electrical supplies. Gradually all submarines came to be equipped with oxygen candle generators and carbon dioxide absorption units.

There the matter rested until the advent of the nuclear submarine in the early sixties. Their very long dived endurance dictated that a coherent air purification philosophy be adopted, rather than the *ad hoc* arrangements characteristic of conventional submarines of the time. Latterly the increasing capabilities of conventional boats mean that they must now be brought more into line with nuclear practice.

Basis of Air Purification

The gas constituents of a normal atmosphere are given in TABLE I. Within the closed space of a submarine hull, this is quickly degraded by the activities listed in TABLE II. If the atmosphere is analysed it will be found to contain a large number of contaminants; anything from lubricating oil to the Chief Radio Supervisor's after-shave will be present in some quantity or another. Experience from industry has indicated that some of these may be harmful if present in concentrations above a limiting amount and this has led to the development of a large number of occupational exposure limits. However these ceilings are unsuitable for submarine use, as they are usually based on a 8-hour working day and a 5-day week; in a submarine the exposure might be continuous over many days. Therefore BR1326[3], which lays down the R.N. practice for submarine air purification, quotes maximum permitted concentrations (MPCs). These have been specifically developed for the purpose and are based on submarine exposure patterns and the monitoring system in use. Each substance has three MPCs—the MPC_{90}, the maximum permitted concentration which can be permitted for 90 days and two emergency limits, the MPC_{24} and the MPC_{60}, which refer to 24 hours and 60 minutes respectively. Oxygen grace time denotes the length of time a submarine can remain dived without supplementary oxygen before the oxygen level falls below MPC_{90}.

The prime method of achieving these limits is by passive control or ensuring that potential toxins are not embarked. It follows that nothing must be used in the construction or operation of the submarine and her equipment that will emit excessive amounts of any toxic substance. This is done by specifying only approved materials from the list in BR1326A[4], the Materials Toxicity Regulations. Nothing may be embarked until it has been checked and entered onto the list. This rule, which was drawn up for nuclear submarines, is now applicable also to UPHOLDER and OBERON Classes. However it is recognized that retrospective implementation in the O Class would impose difficulties in certain instances, so the regulation there is mandatory only for materials new to service.

Where passive methods are insufficient, active control must be resorted to. This involves the installation of equipment to produce oxygen and remove certain agents. In order of importance, the contaminants to be removed from the atmosphere of diesel electric submarines are carbon dioxide, hydrogen, carbon monoxide, hydrocarbons and aerosols. The equipment must function in two very different operational scenarios—normal running, and disabled on the sea bed. This latter case introduces a number of specific problems. The environmental conditions could be adverse and there may be no power supplies available other than manpower. In the R.N., air purification equipment dedicated to the life support of survivors must be able to function correctly at angles up to 45 degrees, in low ambient temperatures, high relative humidity and at elevated ambient pressures. This last point is especially important for in any credible submarine accident the internal pressure within the hull will rise due to the effect of internal flooding and leaks from the various air systems.

TABLE I—*Gas constituents of a normal atmosphere*

Constituent	*% by vol.*	*Partial Pressure at 1 bar* mm Hg
Nitrogen	78.05	593.18
Oxygen	20.90	158.84
Carbon Dioxide	0.03	0.23
Argon	0.93	7.07
Other gases	0.09	0.69

TABLE II—*Activities that degrade the atmosphere*

Activity	*Effect*
Respiration	Oxygen depletion & carbon dioxide production
Smoking	Carbon monoxide and aerosol production
Charging batteries	Hydrogen production
Running machinery	Carbon monoxide, hydrocarbons and aerosols
Cooking	Water vapour, carbon monoxide, fumes
Cooling systems	Refrigerant leaks

Carbon Dioxide Removal

In most submarines the carbon dioxide level will rise to the maximum permitted concentration after about eight hours, the so called grace time. After this period, if the submarine does not wish to snort, some form of carbon dioxide removal will have to be undertaken. This can be either by consumable stores or a regenerative process. The first usually has the advantages of low power consumption and efficiency, against which must be balanced the cost, weight and volume of the material consumed. Regenerable sources will often result in savings of through-life costings and stowage space but will have a higher power requirement. This last point makes them unsuitable for use in disabled submarines, so consumable escape stores are still required. TABLE III lists the various options, the best of which are explained below.

TABLE III—*Carbon dioxide absorbers*

CONSUMABLE SOURCES		
Source	*Advantages*	*Disadvantages*
Soda Lime	Cheap. Readily available. Efficient	Weight. Loses its efficiency at low temperatures
Sodium Hydroxide	Relatively efficient. Low weight	Caking problem. Not easily available at required purity. High gas exit temp.
Baralyme	More effective than soda lime at low temperature	Not as efficient as Soda Lime at NTP. Expensive
Lithium Hydroxide	Very efficient. Works in low temperatures	Dust hazard. Very expensive
REGENERABLE SOURCES		
Source	*Advantages*	*Disadvantages*
Wet MEA Scrubber	Low power	High toxicity of MEA
Molecular Sieves (*a*) Temperature Swing Molecular Adsorber	Low power, dived	Needs water removal. High power during regeneration Limited capacity
(*b*) Pressure Swing Molecular Adsorber	Rapid plant cycling	Space Noise High power required
Solid Amine Scrubber		Needs water for regeneration

Soda Lime

Carbon dioxide absorption units generally consist of a fan unit which draws air through a number of canisters containing soda lime. The unit shown in FIG. 1 is fitted in all R.N. submarines, primarily to provide a means of carbon dioxide removal in the escape compartments of a disabled submarine. Soda lime is mainly a mixture of sodium and calcium hydroxides. When in contact with carbon dioxide, a liquid phase reaction occurs in which the sodium hydroxide is converted to sodium carbonate:

$$CO_2 + 2NaOH \quad \rightarrow Na_2CO_3 + H_2O$$

The sodium carbonate in solution then reacts with the calcium hydroxide to give insoluble calcium carbonate:

$$Na_2CO_3 + Ca(OH)_2 \quad \rightarrow CaCO_3 + 2NaOH$$

In this second reaction the regenerated sodium hydroxide becomes available to absorb more carbon dioxide. The importance of the water must not be ignored as the reaction takes place in the liquid phase. Therefore, if the moisture content is too low, the absorption efficiency will be poor. Although additional water is produced in the reaction, the exothermic nature of the process means that there is a net loss to the air stream. To avoid the canisters drying out and to maximize their efficiency, it is vital that submarine designers site the unit in the most humid conditions possible. The traditional practice of adding water to the canister when half exhausted is not recommended. Although the removal rate initially improves, the water causes the soda lime granules to cake and restrict the air flow. Overall it has a negative effect.

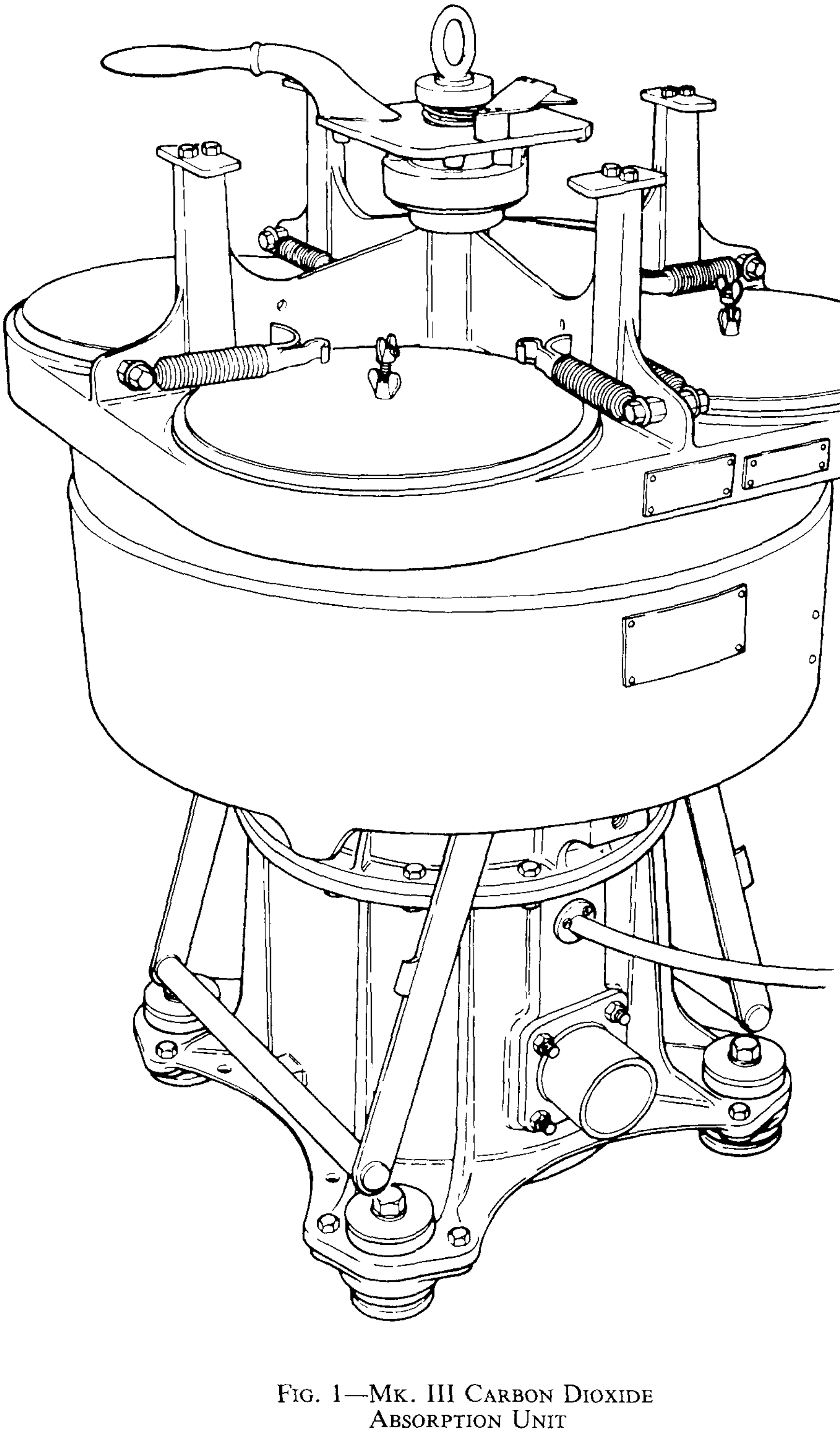

FIG. 1—MK. III CARBON DIOXIDE ABSORPTION UNIT

Lithium Hydroxide

Lithium hydroxide has high carbon dioxide absorption characteristics and a low weight. However when compared with soda lime by volume its advantages are not quite so marked. It also might have problems with dusting. The greatest problem as far as the R.N. is concerned is its cost at about 40 times that of soda lime. Notwithstanding that, it has been adopted by a number of NATO countries.

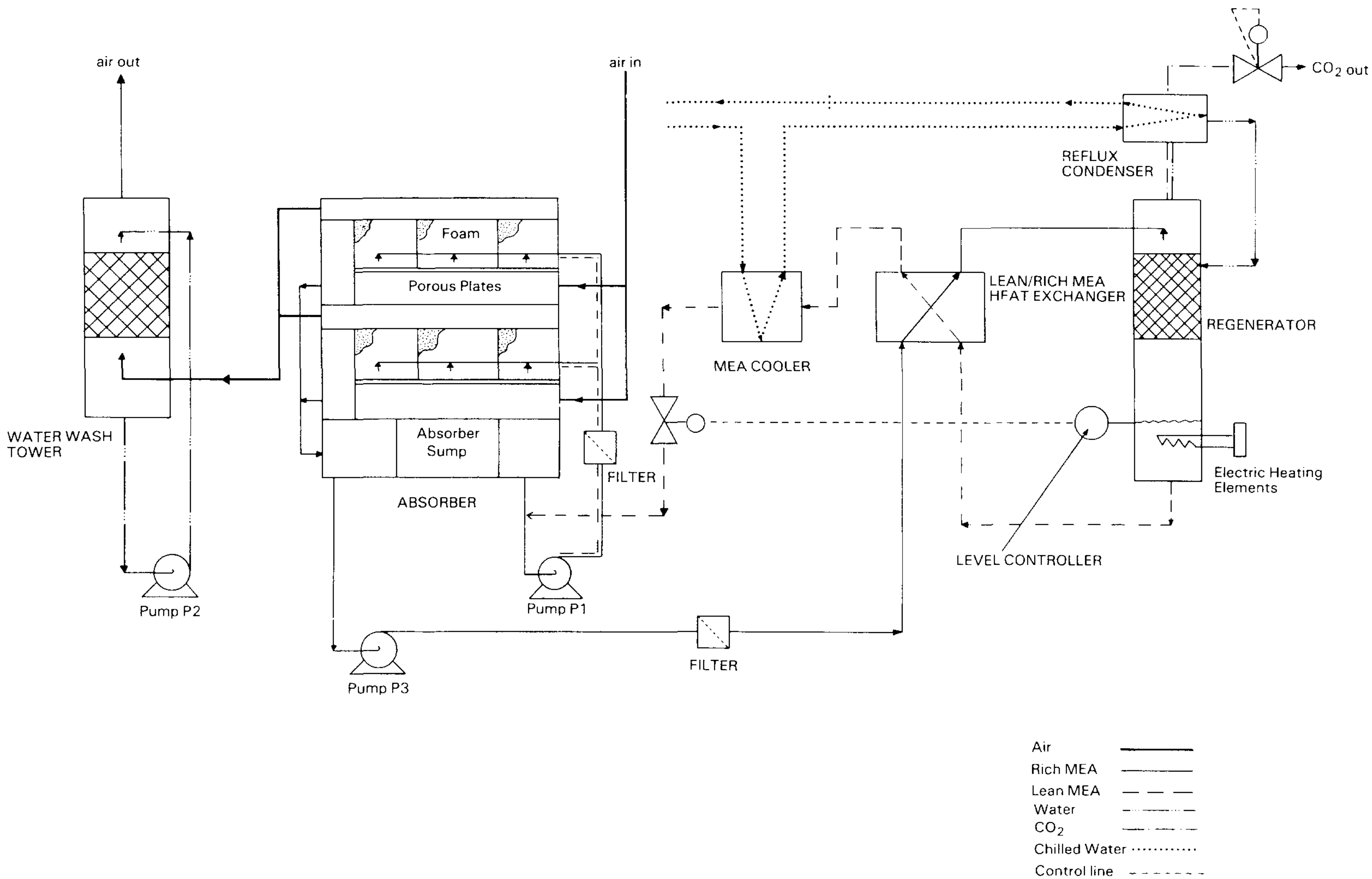

FIG. 2—FOAM BED SCRUBBER SYSTEM USING MONOETHANOLAMINE

Wet MEA Scrubber

Monoethanolamine (MEA) is extensively used by industry to remove carbon dioxide from gas mixtures (FIG. 2). The air requiring scrubbing is passed via a filter to the absorber section of the plant, where it is forced up through a porous plate, on top of which MEA is being sprayed to form a foam bed. The close contact between the air and MEA in the foam bed allows the carbon dioxide to be absorbed before the air is returned to the atmosphere via a water wash. Meanwhile the carbon dioxide rich MEA is pumped to the regenerator where it is sprayed into the top of a packed column and allowed to fall through the packing into the sump where it is boiled. The evolved steam strips the carbon dioxide from the MEA falling through the packing. The lean MEA is passed back to the absorber via a back-to-back heat exchanger. The carbon dioxide is passed to a compressor for discharge overboard. Latterly the U.K. has been building a new generation American-designed plant which replaces the porous plates and the foam bed with a packed tower absorber[5].

Several companies have proposed low-powered versions of this plant for conventional submarines. A unit occupying 1 m^3, with a power consumption of less than 7 kW should be sufficient for a 40-man submarine. A plant of this type is under development in the U.K.

Molecular Sieve—Temperature Swing Molecular Adsorber

These plants work on the principle that air is forced through a bed of zeolites to adsorb carbon dioxide. When the bed is saturated it is regenerated by heat, the carbon dioxide being drawn off by a vacuum pump. Molecular sieves separate mixtures of gases by the selective removal of one compound's molecules. The internal structure of the sieve is like a honeycomb of pores of similar size to the molecule being adsorbed. Pre-dryer beds have to be used to remove water, which would be preferentially adsorbed in the main bed.

Plants based on this process have been used in the first four TRAFALGAR Class submarines for the removal of carbon dioxide and refrigerants. However the high power needed for regeneration makes them unsuitable for conventional submarines. CJB Developments Ltd have proposed a variation of this process for conventional submarines. This utilizes much bigger adsorption beds which are only regenerated when the submarine is snorting and power is available from the diesels. It has the advantage of very low consumption and quiet operation when dived. Obviously the carbon dioxide removal capacity is limited by the size of the bed. A typical installation will give about 18 hours of removal capacity, extending the possible snort interval to 24 hours. For dives longer than this, some kind of consumable source needs to be employed. However, as most credible operating profiles consider the number of extended dives to be strictly limited, this may not be too disadvantageous.

Solid Amine Scrubber

Dornier in West Germany and Hamilton Standard in the United States have both proposed a solid amine scrubber for submarine use. In many ways it is similar to plants using molecular sieves, in that it requires cyclical regeneration (FIG. 3). A blower forces the inlet air through a solid amine bed which absorbs the carbon dioxide. Meanwhile the other bed is regenerated by low pressure steam, which heats the amine bed, stripping out the carbon dioxide before it is discharged overboard. Periodically the beds are changed over. These plants are unlikely to have any significant advantages over the wet type.

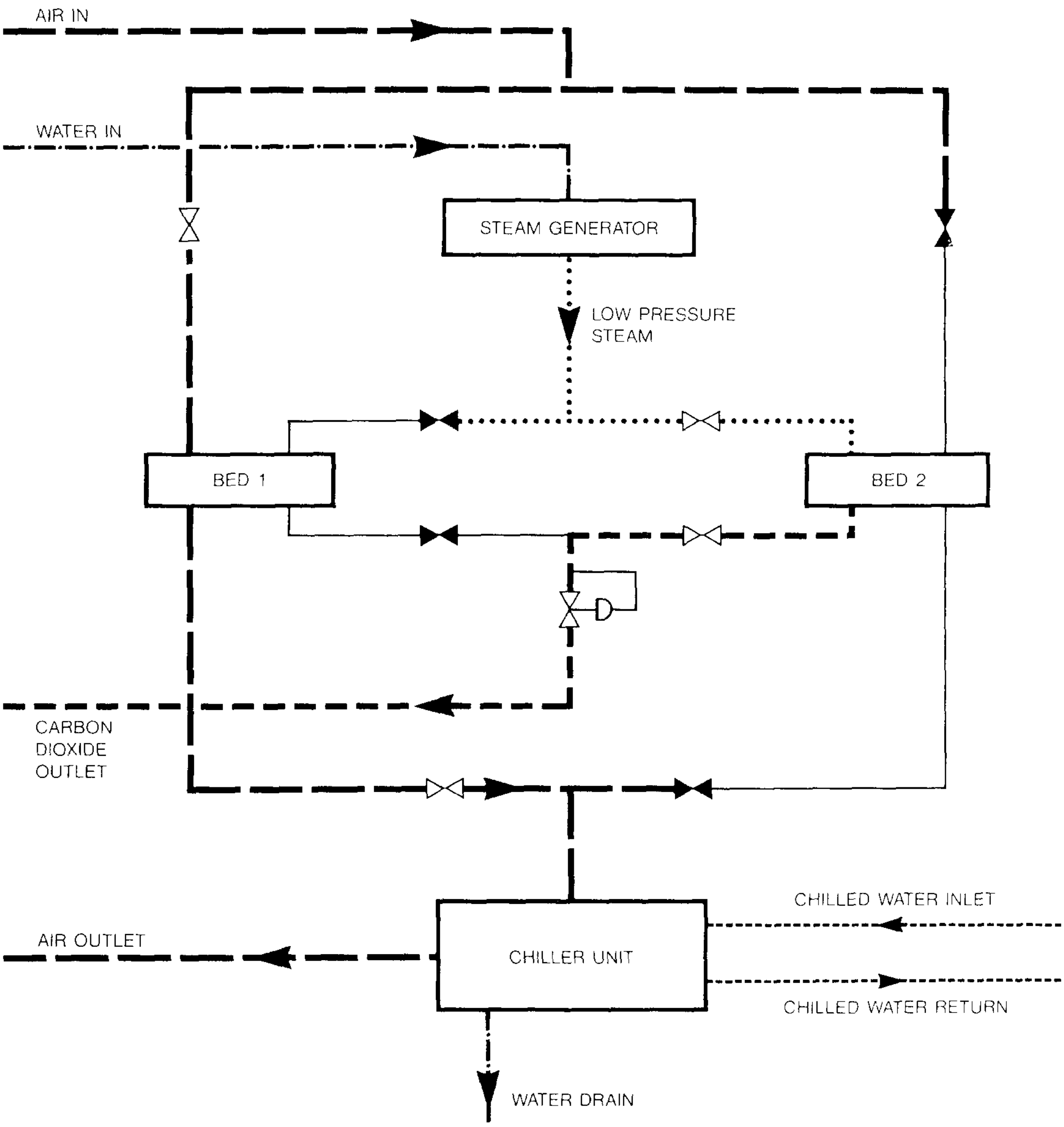

FIG. 3—SOLID AMINE SCRUBBER. A TYPICAL TWO-BED PLANT, WITH BED 1 SHOWN ON-LINE AND BED 2 BEING REGENERATED

Oxygen Production

Most conventional submarines are capable of diving for periods up to 24 hours without additional oxygen provision. As a submarine on transit to or from a patrol will require to snort frequently to maintain a suitable speed of advance, no additional oxygen provision is required for those phases. It is only when the submarine is travelling slowly on patrol that battery endurance permits snorting intervals longer than the oxygen grace time. TABLE IV lists the alternative sources of oxygen, both regenerable and consumable. Consumable sources are, however, sufficient to meet the requirement in conventional submarines.

Liquid Oxygen Storage

Oxygen can be stored as a liquid (LOX) in cryogenic tanks. This method is already successfully used by some European navies to support air-independent propulsion packages. In such submarines it is obviously sensible to include an extra margin for life support. Any designer of a LOX-based system must

TABLE IV—*Possible oxygen sources*

CONSUMABLE SOURCES		
Source	*Advantages*	*Disadvantages*
Physical Storage—Liquid Oxygen	Simple and cheap. Readily available	Size and shape of tank. Safety considerations.
Physical Storage—Gaseous Oxygen	Simple and cheap. Readily available	Weight and volume of pressure vessel. Safety considerations
High Test Peroxide	Can be stored outside the hull. Low volume	Possiblility of runaway decomposition and explosion
Potassium Superoxide	Also removes Carbon Dioxide. Compact. Currently used by Italians and Soviets	Explosive in a fire or in contact with water. Expensive
Sodium Chlorate	Efficient. Low volume.	Enhances any fire. Manpower-intensive
Oxygen Candle	No external power needed. Current R.N. source	
REGENERABLE SOURCES		
Source	*Advantages*	*Disadvantages*
Extraction from sea water	No need to carry consumable stores. Potential for low volume	High power pumping requirement. Small concentration of oxygen in some areas of the sea. High risk development
Electrolysis of water	Mature Technology. Significant RN operating experience	High power requirement. Very high initial cost. Complex systems

bear in mind the well documented hazards associated with LOX. Nevertheless there is extensive commercial experience in this area and no insurmountable difficulties exist. In the past it was always considered that a LOX system was unacceptably dangerous in a fire, but modern triple insulated tanks are well able to withstand any credible fire that would not already have led to the total loss of the vessel.

Gaseous Oxygen Storage

The weight and volume of the pressure vessel do not make this a viable option if standard methods of submarine construction are used. However the Italian 'GST' midget submarine has a hull constructed of a series of circular tubes welded together, the inside of each tube being devoted to gaseous oxygen storage. Although primarily designed for use by the main propulsion system, such oxygen could be adopted for life support.

Oxygen Candles

Sodium chlorate, when exposed to heat, will reduce to produce sodium chloride and oxygen:

$$2NaClO_3 \longrightarrow 2NaCl + 3O_2$$

The heat can be supplied by several means, the usual method being the burning or oxidation of iron powder:

$$2Fe + O_2 \longrightarrow 2FeO + heat$$

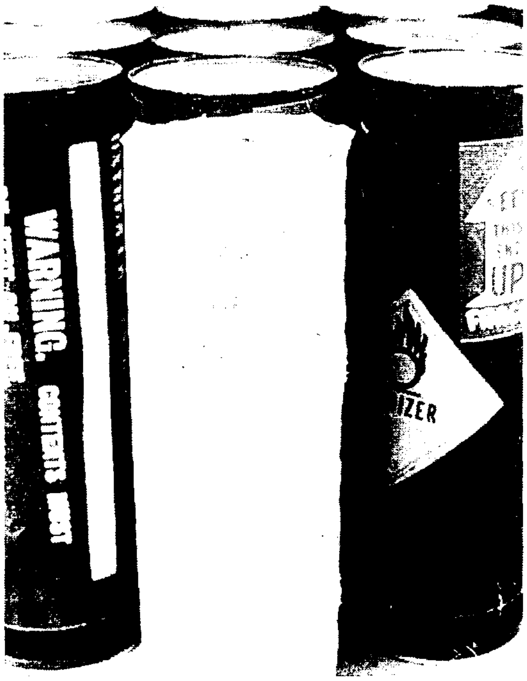

FIG. 4—R.N. MK.V OXYGEN CANDLE

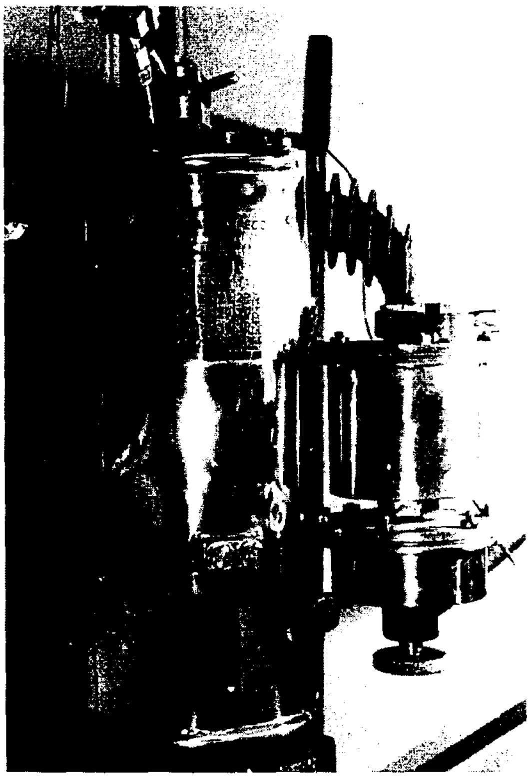

FIG. 5—R.N. OXYGEN GENERATOR

The current U.K. candle shown in FIG. 4 is primarily a mixture of sodium chlorate, iron powder and barium peroxide and uses both reactions. It is cylindrical in form, 380 mm high and 114 mm in diameter and produces about 2 cubic metres of oxygen at STP. It is quite stable at room temperatures and oxygen is produced by inserting it into the generator shown in FIG. 5 and igniting the first stage with an ignition cartridge. The oxgen is given off via a series of filters. The function of the barium peroxide is to remove any traces of toxic chlorine gas:

$$BaO_2 + Cl_2 \longrightarrow BaCl_2 + O_2$$

It should be noted that oxygen candles are a very efficient form of storing oxygen. Volume for volume they are equivalent to a bottle of oxygen at 6000lb/in^2 and, as they are not dependant on any external power supply, they are ideal for use in disabled submarines.

Electrolysis of Water

Electrolysis is used in all R.N. nuclear submarines. There are two models in service, the original high pressure electrolyser and the new solid polymer low pressure type. Both types have far too high a power requirement to make them suitable for conventional submarines.

Removal of Other Contaminants

Carbon Monoxide and Hydrogen

British diesel-electric submarines are equipped with hydrogen eliminators (FIG. 6) for the removal of the hydrogen evolved from the main battery. These small catalytic burners are fitted into the deckhead throughout the submarine and catalytically oxidize the hydrogen to water vapour. A convective air flow over the catalyst is promoted by a small low wattage heater. Despite their name, these units also remove a significant quantity of carbon monoxide.

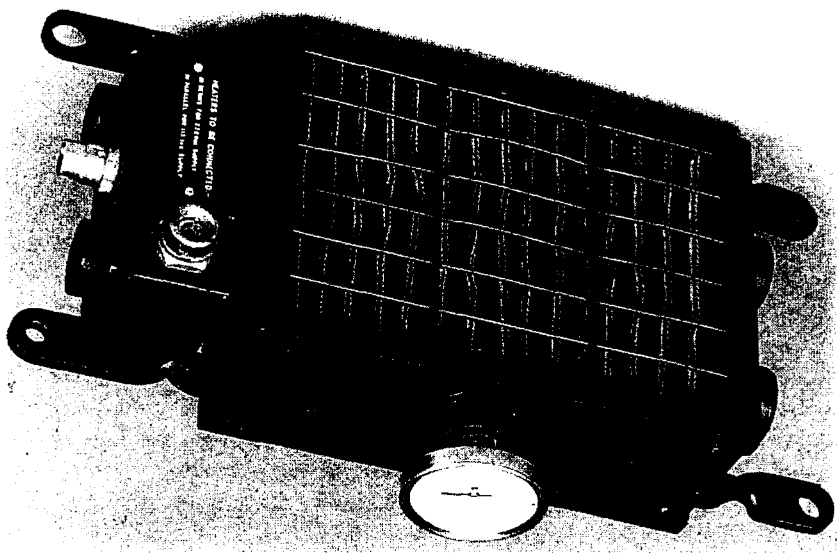

FIG. 6—HYDROGEN ELIMINATOR, NORMALLY MOUNTED IN THE DECKHEAD

A number of commercial proprietary catalysts are now available for the oxidation of both hydrogen and carbon monoxide. Removal units based on these precious metal catalysts have been developed for installation in submarine ventilation systems but poisoning of the catalyst remains an inherent problem. Most European submarine designs place large low temperature catalytic burners in the ventilation return from the main battery, instead of the R.N. practice of using small units distributed throughout the boat.

Organics and Vapours

Activated charcoal made from coconut shells is used in the R.N. to absorb organics. The important properties of various charcoals to be considered are activity and retentivity. The activity is defined by the following test. A sample of charcoal is subjected to a dry air stream in equilibrium with carbon tetrachloride vapour. Once the charcoal is saturated it will no longer increase in weight. The activity is specified as the mass of CCl_4 adsorbed divided by the mass of charcoal. The retentivity is specified for a particular absorber by first carrying out the absorption test and then passing dry clean air over it until it shows no reduction in weight. The retentivity is defined as the weight of CCl_4 retained divided by the weight of charcoal. Typical figures for suitable charcoals are in the order of 60% for activity and 40% for retentivity.

Dust Particles and Aerosols

Dust and aerosols are removed by use of filters fitted in the ventilation system. Regular cleaning is required to keep them effective.

Design Considerations

All submarine designs are the result of compromise. The conflicting requirements of food and fuel endurance, speed, complement and dived endurance all have to be catered for. As in all other cases, the starting point for the designer of the air purification and ventilation system must be the staff requirement. Apart from listing the required patrol length and the dived endurance, this document must indicate the intended operational profiles. These detail the various types of patrol the submarine should be capable of undertaking. They should list the amount of time she will be in transit to and from the operational sector and her employment whilst on patrol. From this the designer can extract the duration of all periods spent dived between snorts for each profile.

Selection of the Carbon Dioxide Removal System

The usual way to select the system to be used is first to evaluate the consumable options and then compare the preferred system with the regenerable options. Having obtained the dive profiles, the designer needs to calculate the carbon dioxide grace time or the length of time a submarine can go between snorts without using a carbon dioxide removal facility. This figure is a function of complement and floodable volume and for a typical submarine is about 8 hours. The routine air purification requirement for a patrol is the sum of the number of hours spent dived in excess of the grace time.

Having derived the air purification requirement, the amount of consumable stores and the associated fixed equipment required to meet this requirement can then be calculated for each option. To this must be added the amount of consumable stores needed to fulfil the escape requirement. The R.N. specifies seven days duration in each escape compartment for this duty. The various choices are then evaluated and the preferred consumable option selected. This should be on the basis of safety, volume, weight and through-life costing.

If the volume and weight of air purification stores required for routine use are unacceptably large or the costs involved excessive, then a regenerable plant may be considered. In many cases a small plant of this type will be both smaller and lighter and have a lower through-life costing. There will still be a requirement to carry some consumable stores and their associated equipment to meet the escape requirement, as the power to run a regenerable plant is not available in a disabled submarine.

Oxygen Production System

A similar calculation must be done for the oxygen production system. However, due to the much longer oxygen grace time, it is unlikely that regenerable methods will be attractive for conventional submarines.

Other Contaminant Removal Systems

For carbon monoxide and hydrogen removal, there is no real alternative to the low temperature catalytic burner; all the other options require too much power. The system's capacity must be sufficient to meet the main battery evolution rate and maintain the proportion of hydrogen in the atmosphere below 2% by volume. A limit of 1% should be the target. Carbon monoxide levels should be maintained below 15 volumes per million (0·0015%). Despite the lower production rate of carbon monoxide, compared with hydrogen, this requirement is the more limiting due to the MPC being several orders of magnitude lower. The performance of all low temperature catalysts falls off due to poisoning by hydrocarbons, so sufficient reserve capacity must be installed to meet this.

Carbon filters, to remove hydrocarbons, organics and smells, must be installed over oil and sanitary tanks, and in the heads (WCs). In long-diving submarines, consideration should be given to installing carbon filter banks in the main ventilation system.

Dust filters should be incorporated into every ventilation return. The design must facilitate easy removal for cleaning.

Royal Navy Developments

H.M.S. *Upholder*, the name ship of the new class of conventional submarines entering service, uses existing consumable stores. The design has been tuned to achieve a suitable combination of speed, dived endurance and patrol length within the constraints imposed by cost, size, battery capacity, food and fuel. Nevertheless it is apparent that, by using more modern techniques, considerable improvement could be made to the air purification equipment.

A specific deficiency with regard to carbon monoxide removal has already been identified during contractor's sea trials.

Oxygen Candles

Two parallel projects are under way in this area. The first concentrates on the development of a replacement oxygen generator for burning the present type of oxygen candle. This new unit is constructed of stainless steel and will be much cheaper to manufacture than the present one. Its main advantage is that by having a much larger oxygen outlet and filter bed, it will be less prone to blockage and bursting disc failure.

At the same time, a new square section self-contained oxygen candle is under development. This new candle (FIG. 7), is burned in its storage canister and contains an integral filter. As there is no requirement to handle the candle mixture itself, it should be much less prone to damage in transit. Initial results are encouraging and it is hoped to conduct a minor sea trial of both items soon. On completion, a decision will be taken on which system to adopt.

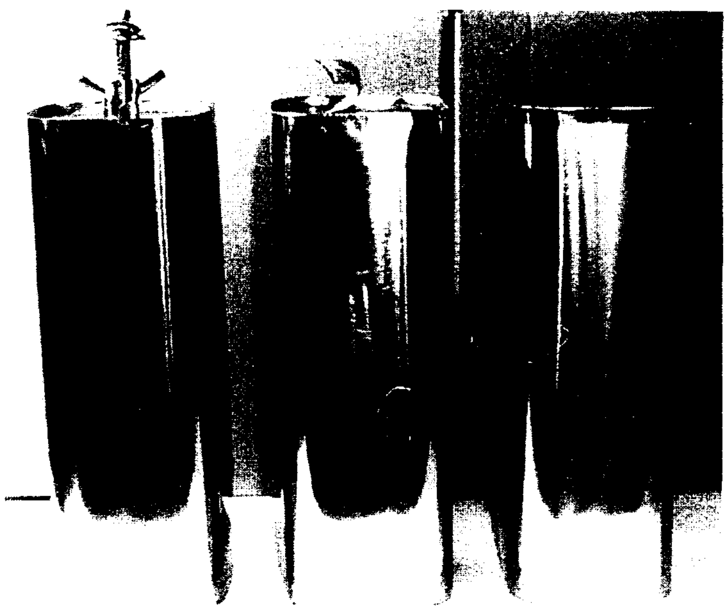

FIG. 7—PROTOTYPE SELF-CONTAINED OXYGEN CANDLE

Carbon Dioxide Absorption Unit

A new Mk.V carbon dioxide absorption unit (FIG. 8) has been developed and is undergoing trials at ARE (Alverstoke). This unit is much more sophisticated than the existing marks, which were first introduced in 1943. To meet the escape requirement it is designed to operate in compartment pressures up to 5 bar and is capable of man-powered operation via a bicycle drive. It is intended to replace the existing units and emergency carbon dioxide foot-pumps in all submarines.

New Soda Lime Canister

A prototype Mk. IV soda lime canister (FIG. 9) has been developed for use in conjunction both with the existing carbon dioxide absorption units and with the new Mk.V. It has a much lower linear air velocity in the absorption bed and is consequently much more efficient. Its square shape should make it easier to store, whilst its small cross-section allows disposal via the gash ejector. A minor sea trial will soon be conducted.

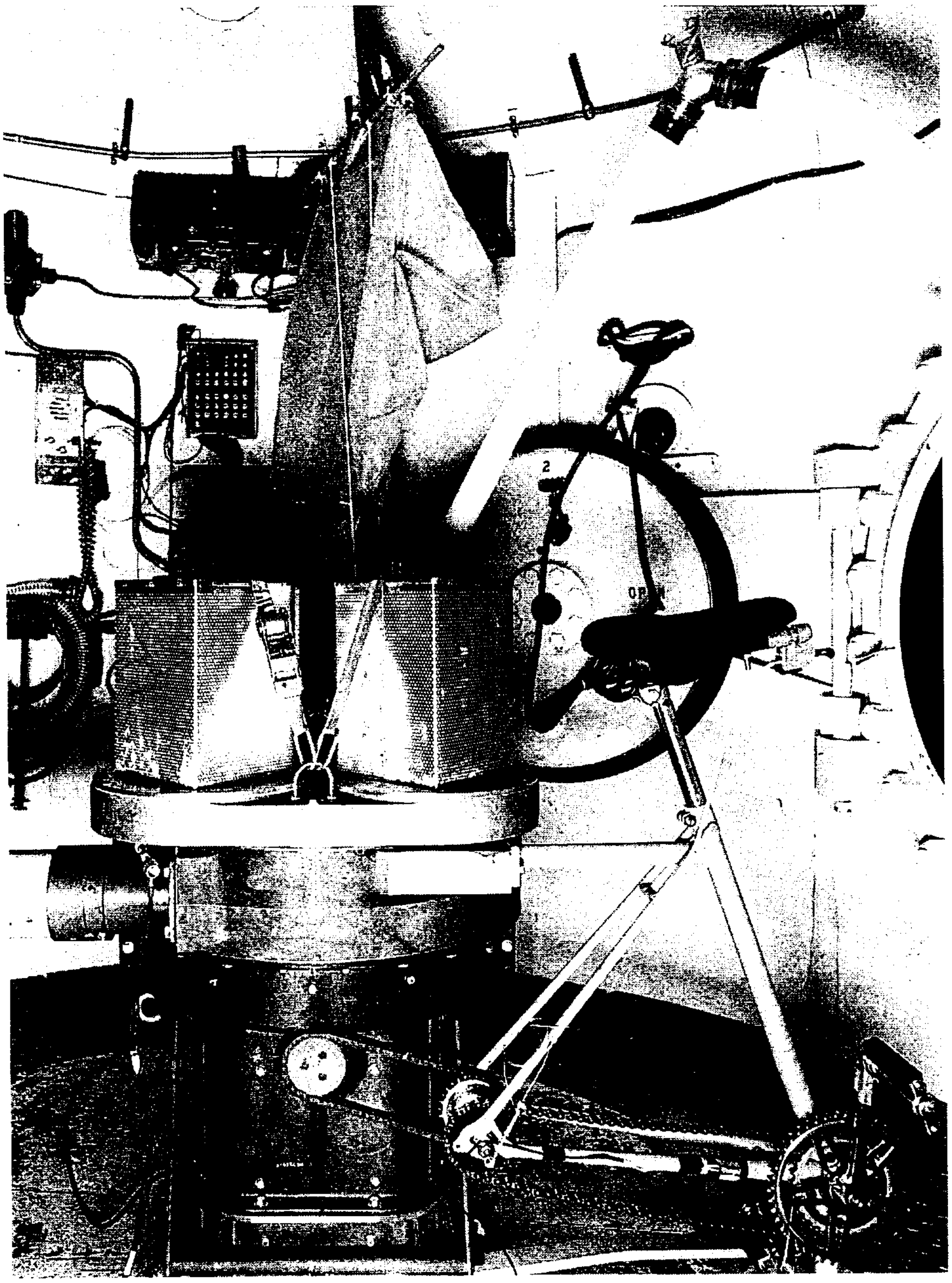

FIG. 8—THE PROTOTYPE MK.V CARBON DIOXIDE ABSORPTION UNIT UNDERGOING TRIALS AT ARE (ALVERSTOKE) TO TEST ITS PERFORMANCE AT ELEVATED PRESSURE

Carbon Monoxide Eliminators

Approval is being sought either to develop a new low-powered carbon monoxide/hydrogen eliminator or to modify the existing unit so as to improve its abilities with regard to carbon monoxide. Pre-feasibility studies, conducted by ARE (Holton Heath) have demonstrated the ability of a number of commercially available precious metal catalysts to meet the duty. Until this work is complete, the UPHOLDER and OBERON Classes will continue to operate, on occasions, outside the limits laid down in BR1326.

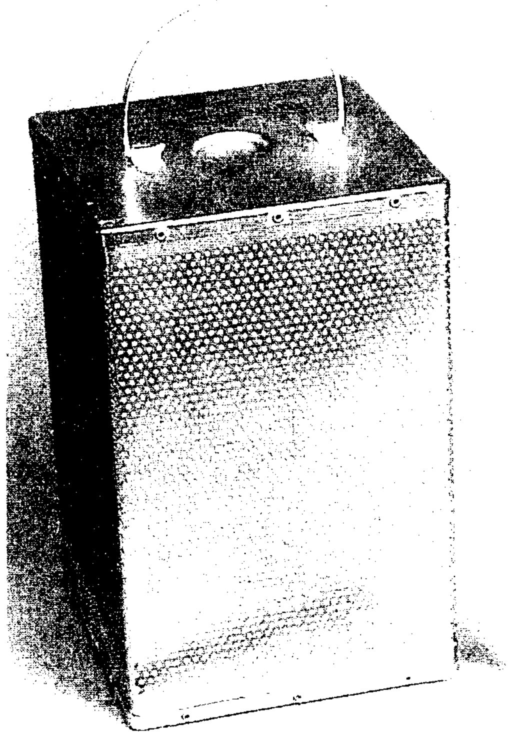

FIG. 9—PROTOTYPE MK.IV SODA LIME CANISTER

Conclusion

The subject of air purification in submarines has such wide implications, that it has not been possible to give anything other than a brief introduction to the subject. Nevertheless it is the author's view that all too often it has been considered far too late in the specification and design of submarines, with haphazard results. Tighter atmosphere limits and increasingly more capable submarines make this approach unacceptable. If a balanced design is to emerge, the air purification aspects must be considered early in the specification and design.

The new carbon dioxide absorption unit and the new soda lime canister will do much to enhance the chances of survivors in a disabled submarine and prove more reliable and user-friendly in routine service. Similar expectations exist for the new oxygen generator or self-contained candle.

Acknowledgement

The author would like to acknowledge the assistance of Commander B. Forbes who identified many of the historical references.

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