

THE USE OF SCRUBBERS IN SUBMARINES

REMOVAL OF CO₂ BY MEA

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ABSTRACT

Monoethanolamine (MEA) has been used as a medium for continuous removal of CO₂ from the atmosphere of nuclear submarines in the Royal Navy since H.M.S/M. *Dreadnought*. Surprisingly, the process by which such plants operate has not been fully appreciated or exploited. A new MEA scrubber of American design and much improved performance will come into service in the near future. Spurred by this improvement, a design review of the older plant has revealed certain process changes by which its performance could be uprated.

Introduction

For a nuclear submarine to operate with complete freedom, it must not be constrained by having to return periodically to the surface to ventilate. To achieve this, effective atmosphere control must be performed on board. The two main requirements for such control are to produce oxygen and remove carbon dioxide, the two gases involved in respiration. One method by which carbon dioxide can be removed as a continuous process is by harnessing the properties of a member of the amine family, such as monoethanolamine (MEA), which will absorb CO₂ when cool and release it when hot. Using this property a plant can be constructed whereby CO₂ is absorbed from the atmosphere by cool MEA which when subsequently heated will release its charge of CO₂ for disposal in some way. This article is concerned with the use of such plant in the Royal Navy.

In all nuclear submarines from H.M.S. *Dreadnought* to the last of the *Swiftsure* Class, CO₂ removal has been performed by an MEA-based CO₂ scrubber. Following a short departure with the use of alternative techniques for removal, SSN17 onwards will yet again be fitted with an MEA scrubber, this time of an improved U.S.N. design built under licence in Britain. Despite the obvious importance of this plant, its operation remains something of a black art. To anyone who has operated the amine scrubber certain recurrent defects will be all too familiar. Typical process problems associated with the degradation of MEA are ammonia production, darkening of the solution, and foaming of the absorbant, frequently resulting in loss of CO₂ removal capacity and carry over of MEA into the submarine atmosphere. Mechanically, failure of the CO₂ compressor used for disposal of the gas remains top of the S2022 charts.

Surprisingly, in many cases where degradation reports have been supported with an amine sample for full chemical analysis, the presence of extensive degradation has not been confirmed. A concentrated solution of amine can exhibit the properties commonly associated with degradation. In one case an extremely black viscous sample of amine returned from an operational submarine, when restored to its correct strength by simple dilution with distilled water, was shown to be a perfectly serviceable solution. Further, the process by which the scrubber operates is not widely understood and in particular the sensitivities of that process are not appreciated.

Spurred by the superior performance of the U.S.N. plant, a review of the older Royal Naval plant has been completed. Certain simple process changes have been highlighted by which the performance of these plants could be improved and it is hoped in the near future to perform land-based trials to prove these potential improvements and develop subsequent modifications for in-service plant.

This article focuses on the operating principles of the amine scrubber to show what improvements may be possible and it highlights areas which require vigilance by operators in order to achieve optimum performance from the plant. Unfortunately there is little the operator can do once at sea to change the process parameters of the plant and often he must watch rather frustratingly as the Command complains about high CO₂ levels in the submarine.

Sources of Carbon Dioxide and Atmospheric Limits

Carbon dioxide is present in fresh air at volumetric concentrations of around 0.03%. An alternative way of expressing this concentration is in terms of partial pressure. The partial pressure is that pressure which a constituent gas of a gas mixture would exert on a vessel if it occupied that vessel in isolation. The partial pressure can be simply calculated as it is the product of the absolute pressure and volumetric concentration. Hence a volumetric concentration of 0.03% carbon dioxide at an absolute pressure of 760 mm Hg exerts a partial pressure of 0.228 mm Hg.

Partial pressure is important since it is this property of a gas which provides the driving force for certain important reactions. In respiration, for example, it is the partial pressure of oxygen which provides the driving force for oxygen to pass through the membrane wall of the lung into the blood stream and it is the difference in partial pressure which allows carbon dioxide to pass out of the bloodstream into exhaled air. As will be described later, it is the partial pressure of carbon dioxide which provides the driving force for its removal from a submarine atmosphere by chemical means as employed in the MEA scrubber.

TABLE I—*Physiological Effects of CO₂*

<i>Partial Pressure Carbon Dioxide (mm Hg)</i>	<i>Effect on Man</i>
<7.6	No observed effects
7.6 to 15.2	Slight increase in depth of respiration with headache and fatigue.
22.8	Severe headache with diffuse sweating and dyspepsia. There is a marked loss of efficiency
30.4	Flushing of face. Palpitations
45.6	Hard work impossible. Visual disturbances
60.8	Tremors, convulsions, coma and death

Returning to the concentration of carbon dioxide in air, fresh air, and hence inhaled air, contains CO₂ at a partial pressure of 0.228 mm Hg. Exhaled air contains carbon dioxide at a partial pressure of 23 mm Hg (3.03% at 760 mm Hg). Under normal conditions this exhaled gas disperses throughout the atmosphere to be removed by various natural processes.

On board a submarine however, in a closed environment, the volume into which the gas can disperse is limited and there is no natural process for its removal. Unless action is taken, carbon dioxide levels will rise continuously.

Increasing the partial pressure of carbon dioxide affects the body physiology. Clearly as the partial pressure rises, the driving force for CO₂ removal from the bloodstream falls. The body compensates for this by automatically increasing the respiration rate. The body cannot however compensate indefinitely. Breathing increased concentrations has been observed to have the effects listed in TABLE I.

Clearly there is a requirement to set a limit for concentration of CO₂ in manned spaces. In submarines where personnel are expected to conduct extended patrols, a limit known as the Maximum Permissible Concentration for continuous operation for 90 days, or MPC₉₀ is set. This limit takes into account long-term effects in addition to those effects described in TABLE I and is currently set at 7.6 mm Hg or 1% at 760 mm Hg.

For short periods higher concentrations can be withstood and in an emergency, for example following a fire, an emergency exposure limit is set at 22.8 mm Hg or 3% at 760 mm Hg.

Evolution of CO₂ Removal Equipment

In 1778, during the American war of independence, David Bushnell planned to sink the British blockading fleet with his new invention, the *Turtle* (FIG. 1). This was a small submersible about the size of a large barrel, propelled by means of a horizontal and a vertical propeller and powered by its single occupant. Its weapon was an explosive charge attached to a screw.

The pilot was to manoeuvre underneath his target and attach the charge to the hull. The mine would then be primed and the *Turtle* would retreat.

Sergeant Ezra Lee was the willing volunteer for the first mission. It was not a success and on his return he reported that he was unable to attach the charge due to the copper sheathing on the Royal Naval ships. However, records indicate that the vessels blockading North America at that time were not copper sheathed.

Upon going to closed boat conditions, the CO₂ level in the *Turtle* would rise. It is estimated that Sergeant Lee would have reached our current MPC₉₀ after only five minutes. He would have reached our current Emergency Exposure Limit after fifteen minutes and would have been incapable of operation after forty minutes. It is far more likely that the first submarine attack failed and had to be aborted due to lack of atmosphere control.

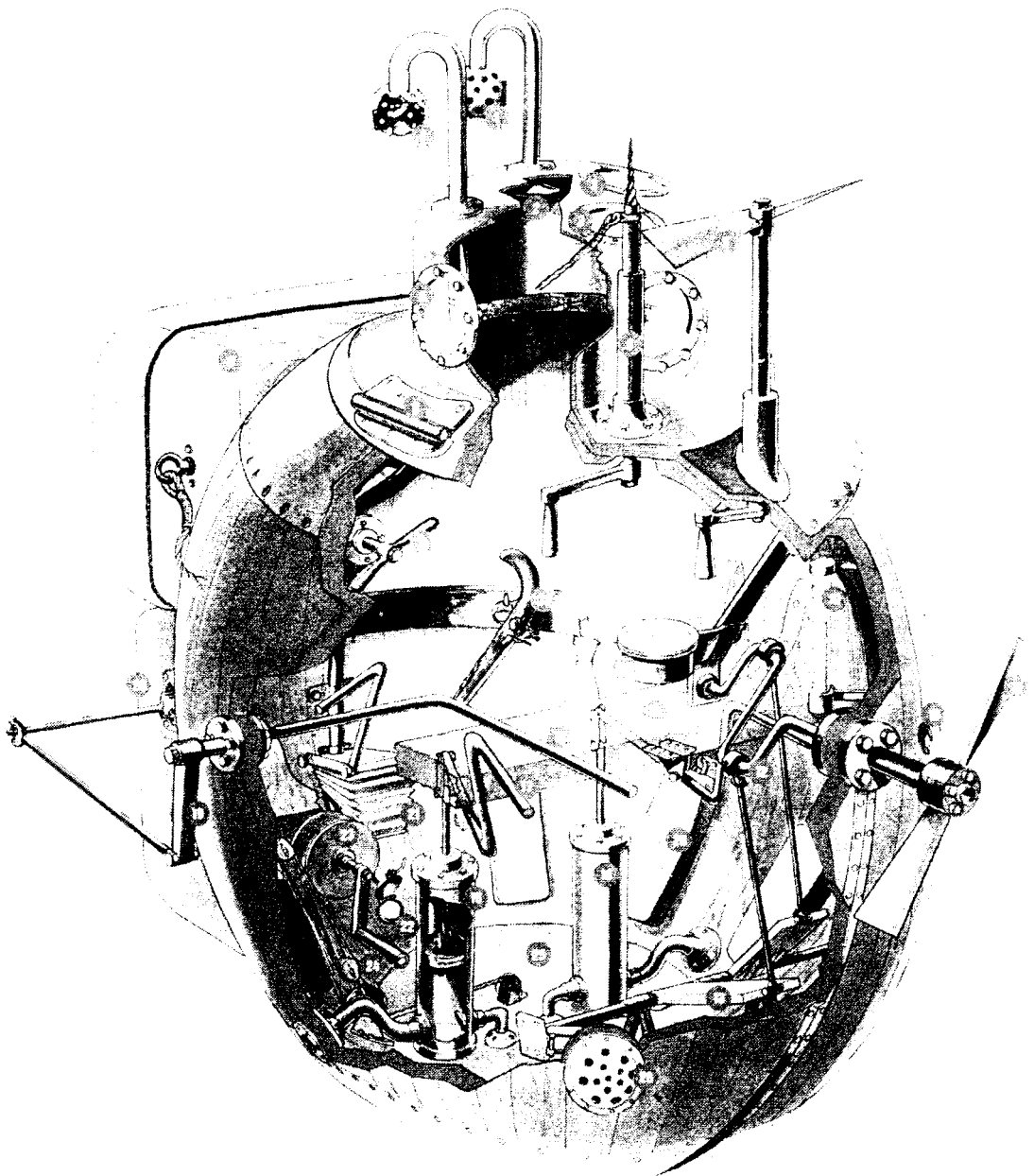


FIG. 1—THE AMERICAN 'TURTLE', 1778: A RECONSTRUCTION BASED ON CONTEMPORARY INFORMATION

Key to relevant items:

1. Ventilation pipes with self-sealing valves to prevent water entering
21. Ventilation pump to force fresh air in and hence foul air out at 2.

Up to World War Two, submarines were really only submersibles. They carried relatively small crews and their dived times were limited. There was also little regard for the long-term effects of exposure to high levels of CO₂. For the dived times required, the CO₂ level in submarines would not rise to levels where crews were incapacitated and so there was no requirement for a CO₂ removal system.

During World War Two, Royal Naval submarine operations extended into waters off northern Norway¹. To avoid detection submarines would charge their batteries at night on the surface and dive during the day to avoid air attack. During summer months, submarines were required to operate in nearly 24 hour daylight and hence were threatened with continual air attack. Often submarines missed the opportunity to charge their batteries and had

to remain dived for periods of sixty hours or more. In addition to the obvious requirement for battery capacity, there was also a need for some form of air purification including carbon dioxide removal. The solution was the carbon dioxide absorption unit. This device consists of a small fan which can be mounted with canisters containing soda lime. Soda lime is a mixture of calcium hydroxide, sodium hydroxide and calcium carbonate, which when exposed to carbon dioxide react irreversibly to remove the gas. Hence air drawn over soda lime is scrubbed of carbon dioxide. By the use of this simple system, a small amount of soda lime could be used to give vital extra hours to a submarine's dived time.

Following World War Two, the conventional submarine was largely superseded by the nuclear submarine. There was now the potential to operate for extended periods remote from the surface. The dived time was increased from tens of hours to tens of days. To support an SSN for a two month patrol would have required approaching 20 tons of soda lime. This would clearly have been a severe constraint on operations had the soda lime system simply been scaled up.

The need was recognized for a regenerative CO₂ removal system, which could operate continuously. In this way carbon dioxide from the submarine atmosphere could be removed at the same rate as it was produced, collected and disposed of in some way. Such equipment had been used in commercial gas treatment facilities since the early 20th century. Typically these processes employed a liquid reagent from the amine family. One method of manufacturing bulk carbon dioxide is to burn a hydrocarbon fuel to produce CO₂-rich air. The CO₂ is then separated from the air by the amine process. CO₂ is still produced in this way for certain parts of the brewing industry.

The CO₂ removal equipment of the large scale industrial plant was scaled down and fitted in submarines. The details of this plant and a discussion of the problems associated with it is the subject of the remainder of this article.

Before leaving this historical survey, the use of molecular sieves to remove CO₂ should be mentioned. In the early 1970s, it appeared that the MPC₉ would be reduced to 3.8 mm Hg. The amine plant then in service could not achieve this. The U.S. Navy proceeded to upgrade their amine plant. The Royal Navy, however, opted for the use of an alternative process based upon a family of materials called Zeolites which act as molecular sieves. The basic molecular structure of a Zeolite is a cube. The molecular dimensions of the void in the central area of this cube can be controlled by means of the actual molecular build up of the Zeolite. It is possible to produce a zeolite which has a central void of similar dimensions to a CO₂ molecule and which can trap such a molecule. The capacity of the zeolite to hold or adsorb CO₂ is dependent on temperature and pressure. Hence by cycling these two parameters a process can be developed which will adsorb and desorb CO₂, so producing a continuous CO₂ removal process. This process was used in the temperature swing molecular adsorber or TSMA as fitted in the early TRAFALGAR Class vessels.

By comparison with its U.S. counterpart, known as the MEA Packed Tower or MPT, the TSMA plant did not perform well. The capacity of a TSMA was only just over half that of the U.S. amine plant. Moreover, the TSMA occupied over three times the volume, consumed nearly four times the power and twice the chilled water and also cost considerably more. Since the U.S. amine plant appears to have considerable advantages over the TSMA, a licence to build it in Britain has been obtained and derivative plant will be fitted in SSN 17 onwards.

Hence amine-based plants remain the basic equipment for CO₂ removal in the Royal Navy.

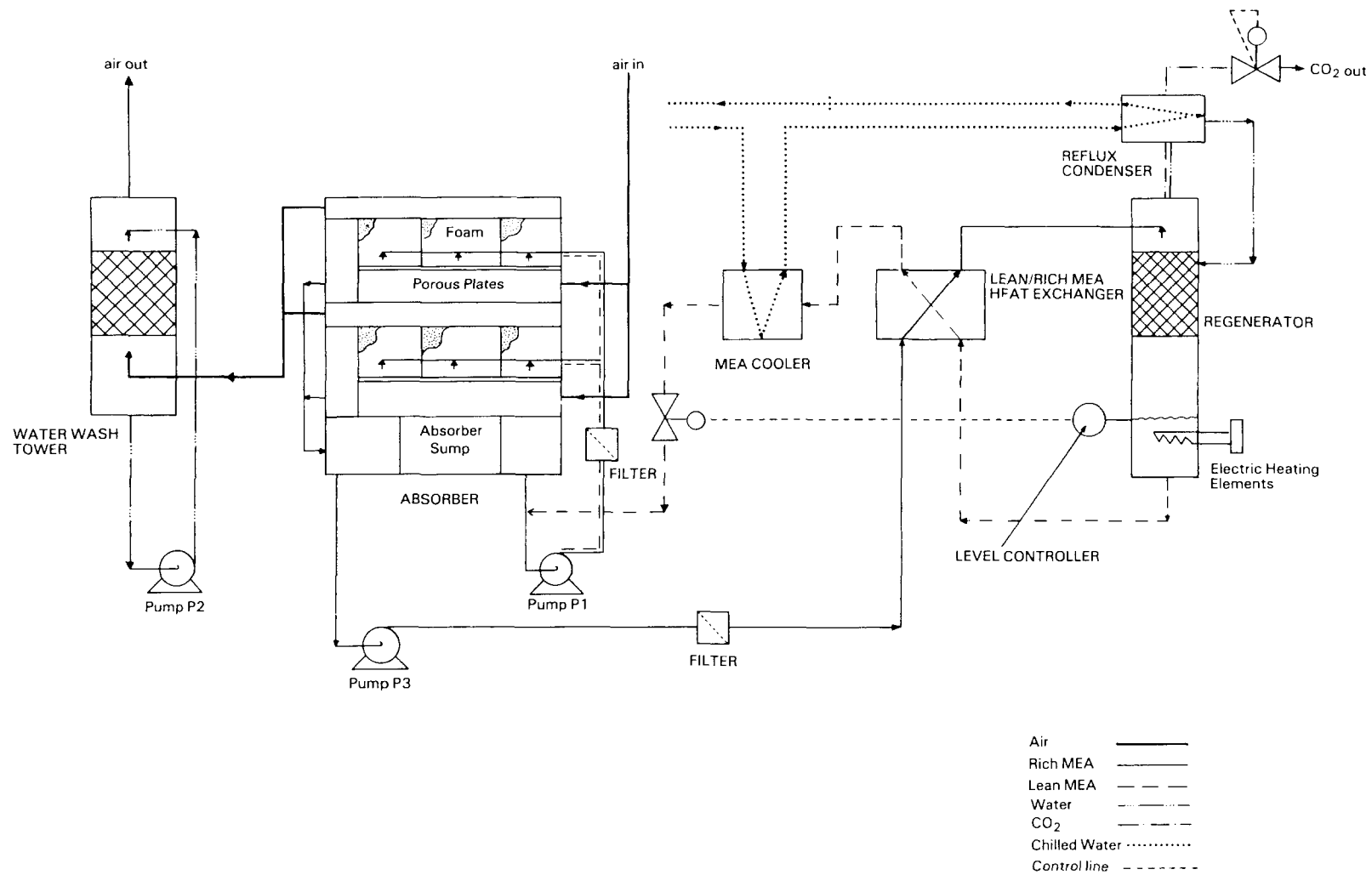


FIG. 2—FOAM BED SCRUBBER SYSTEM

Plant Description

The solubility of CO_2 in a cool solution of MEA is much higher than the solubility of CO_2 in a hot solution of it. Hence if a cool solution is allowed to absorb CO_2 , then by subsequent heating the solution will become supersaturated and will release CO_2 . If the hot solution is then cooled again it is capable of absorbing more CO_2 to enable the cycle to be repeated. This in effect is the basic operating principle of all R.N. MEA scrubber plants.

The scrubber designed in Britain for the Royal Navy in the 1960s is known as the foam bed scrubber. This name arises from the foam bed used to achieve intimate contact between air and amine which results in CO_2 being scrubbed from the submarine's atmosphere.

The design of the latest foam bed CO_2 scrubber as installed in SWIFTSURE Class submarines has changed very little from the original designs installed in VALIANT Class. The plant comprises four basic elements:

- (a) An absorber column where the contaminated air is contacted with the cool amine solution.
- (b) A regenerator column where the CO_2 -rich amine solution is heated and stripped of its CO_2 .
- (c) An amine solution circulation and conditioning system to transfer amine continuously between absorber and regenerator columns.
- (d) A water wash tower to ensure that MEA carry-over in the outlet air stream is removed before the clean air is fed to the ventilation system.

Lean and rich MEA solutions refer to the relative concentrations of CO_2 in solution. A lean MEA solution (low in dissolved CO_2) is produced in the regenerator. A rich MEA solution (high in dissolved CO_2) is produced in the absorber.

The operation of the foam bed scrubber is shown in FIG. 2. Background air, with a CO_2 content of 1% or less, is blown through the absorber section of the plant where it is scrubbed by lean MEA to reduce its CO_2 content. A water wash on the air outlet eliminates any MEA contamination before the air is returned to the ventilation system. The design of the absorber is shown in FIG. 3. Two foam beds are fitted per plant, mounted one above the other and operated in parallel. Foul air enters a plenum chamber beneath each porous plate, while lean MEA is sprayed on top. The air rises through the plate causing a foam to be produced in the MEA where the transfer of CO_2 occurs. Rich MEA subsequently overflows a weir into the sump at the bottom of the tower, to be recirculated back to the absorber sprays. The air outlets from the two absorber beds then combine and discharge through a common water wash tower which removes any solution carry-over from the air. A proportion of the rich MEA solution (about 25%) is taken from the absorber sump and pumped to the regenerator where the absorbed CO_2 is stripped from the solution.

The rich MEA solution is heated in a heat exchanger before entering the regenerator (FIG. 4). Upon entering, the solution is sprayed over a pall ring packing where the CO_2 dissociates from the solution to be swept away for disposal. The MEA percolates down to the liquid sump where it is boiled by electric resistance heater elements to produce steam which rises through the packing to sweep away the dissociated CO_2 . The hot MEA is then returned to the absorber, passing firstly through the MEA/MEA heat exchanger, where it heats the incoming MEA, and then through a chilled water cooler to cool it to the absorber operating temperature. The temperature in the regenerator is set by controlling the operating pressure of the column via a pressure regulating valve on the CO_2 outlet line from the column. The uncondensed CO_2 is collected and disposed of via the CO_2 compressor.

The absorption process is carried out at around 30°C and the stripping process at around 130°C (corresponding to a saturated steam pressure of 30 lb/in², gauge).

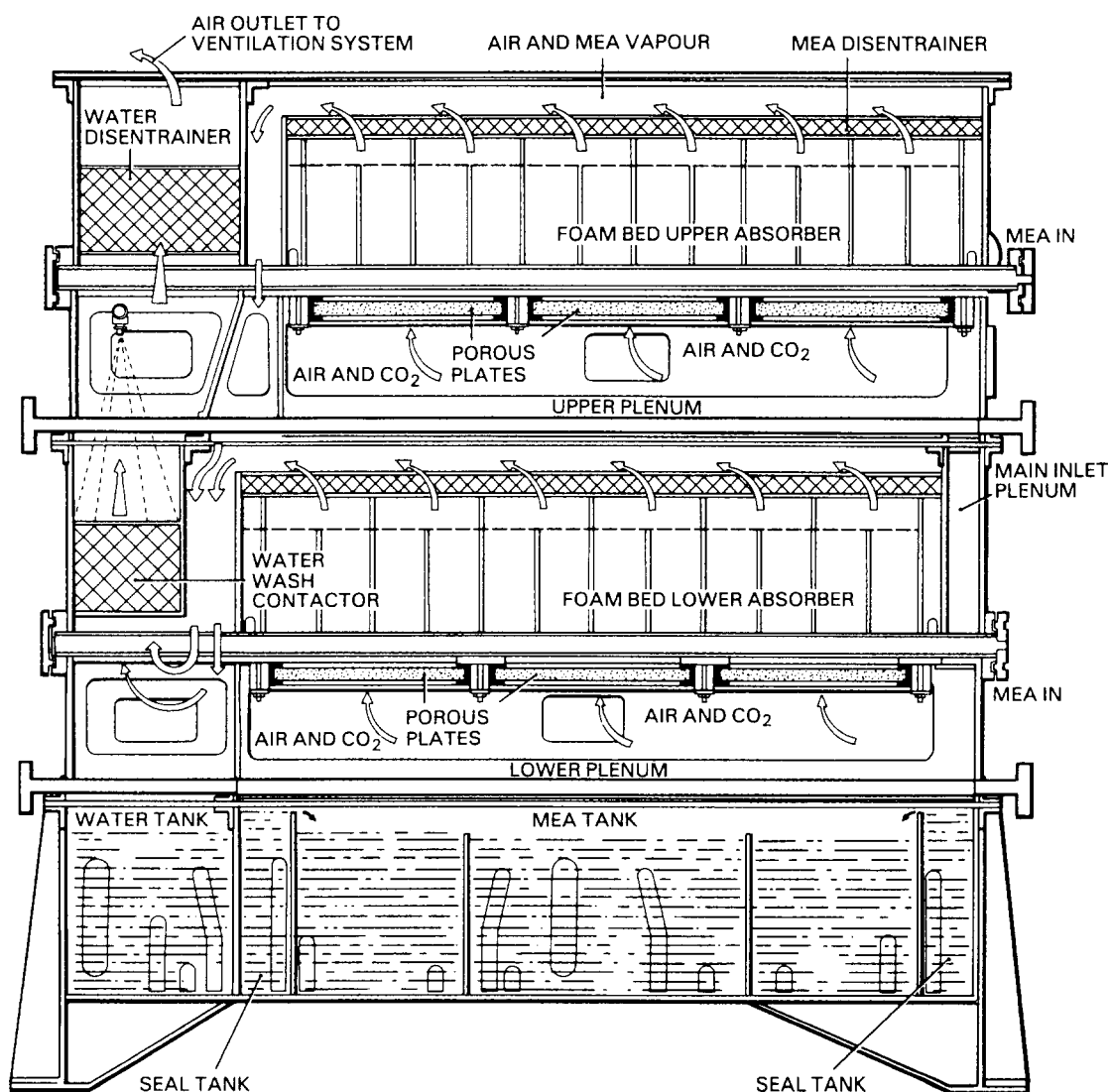


FIG. 3—ABSORBER OF FOAM BED SCRUBBER PLANT

Operating Principles

The operation of an MEA scrubber depends on interphase mass transfer. CO₂ is first transferred from the gas to the liquid phase in the absorber and then back again to the gas phase in the regenerator. The equation describing the rate of CO₂ transfer in either the regenerator or absorber is:

$$N_s = K_g \times A \times (C_2 - C_1)$$

where N_s = mass of solute transferred/unit time
 K_g = overall mass transfer coefficient (on a gas phase basis)
 A = surface area over which mass transfer occurs
 $(C_2 - C_1)$ = difference in CO₂ concentration between gas and liquid phases.

In any given installation the internals of the absorber and stripping columns cannot be changed and so the surface area is fixed. Similarly if flow rates remain constant then, within certain limits of concentration range, K_g remains constant. Hence the transfer rate of CO_2 is dependent only on the concentration difference or concentration driving force.

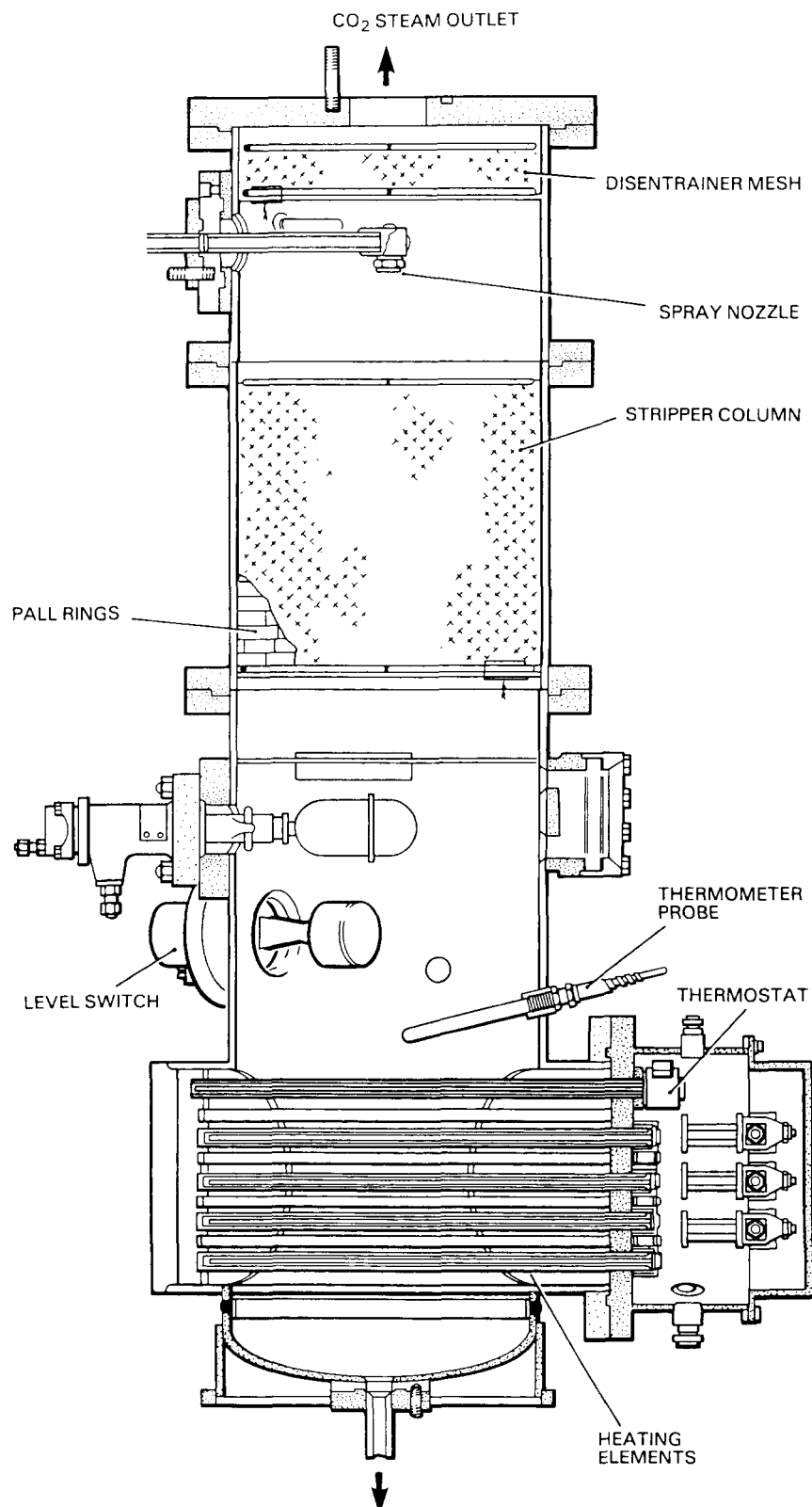


FIG. 4—REGENERATOR OF FOAM BED SCRUBBER PLANT

Both lean and rich MEA solutions contain dissolved CO_2 to a lesser or greater extent and hence both solutions produce a partial pressure (vapour pressure) of CO_2 above the solution. The driving force in the absorber is the difference between the partial pressure of the CO_2 contained in the air and the CO_2 vapour pressure of the MEA solution.

As the background CO_2 concentration and hence partial pressure increases, the driving force increases and so the mass transfer rate increases. The converse applies to low CO_2 background levels. Hence the scrubber will remove a greater mass of CO_2 (lb/hr) at high background CO_2 levels than at lower background CO_2 levels.

An analogous situation occurs in the regenerator column. In this case however, the transfer of CO_2 occurs in the reverse direction, i.e. from solution to vapour. Again the rate is dependant on a CO_2 partial pressure difference, only in this case the CO_2 partial pressure from the rich MEA solution is higher than the CO_2 partial pressure in the stripping steam and hence the CO_2 is transferred from the rich solution to the steam. The richer the MEA solution the easier it is to remove CO_2 , since a richer solution produces a higher partial pressure difference.

The mass transfer processes occurring in both the absorber and regenerator can be represented graphically on driving force diagrams (FIG. 5). On these diagrams the operating line represents the partial pressure of CO_2 in the

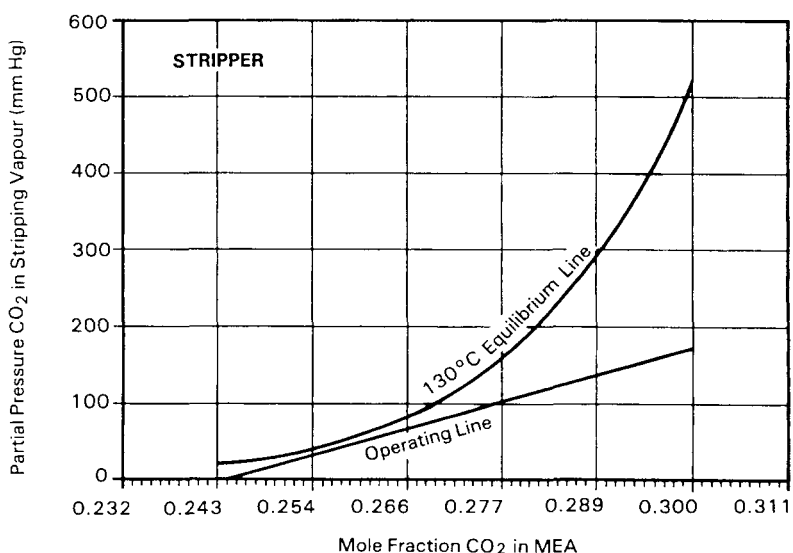
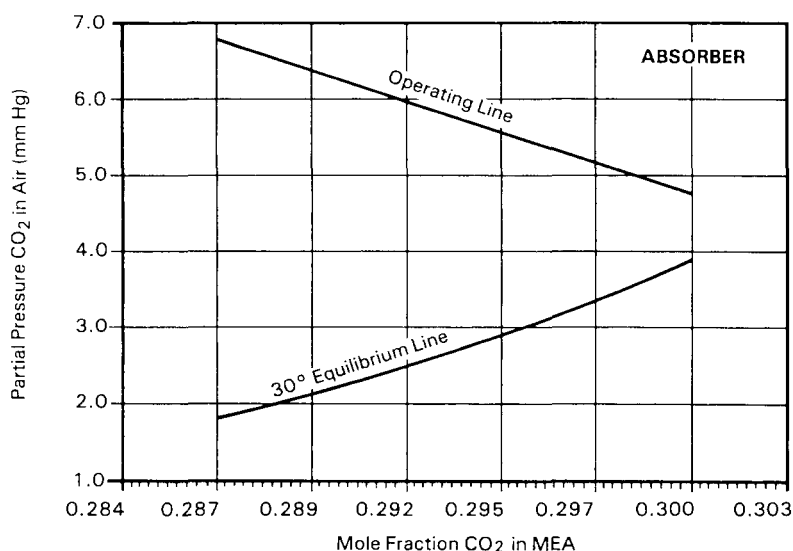


FIG. 5—DRIVING FORCE DIAGRAMS FOR FOAM BED SCRUBBER

MEA as it changes through the column. The equilibrium line represents the equilibrium or saturation CO_2 concentration of the MEA. The vertical difference at any point represents the partial pressure driving force at that point in the column. Note that the absorber operating line lies above the equilibrium line representing mass transfer from the air to the MEA solution, whereas the regenerator operating line lies below the equilibrium line representing mass transfer from the MEA solution to the steam.

It should be remembered that for a given crew complement of a submarine, the production rate of CO_2 is fixed within a certain range, depending upon crew activity. If stable atmospheric concentrations can be achieved with a scrubber operating, that plant must be transferring that rate of CO_2 . The parameter of interest to the operator is the ambient concentration at which equilibrium is maintained, which is governed by the balance of transfer in the absorption tower and regenerator. Hence, a poorly run plant and a well run plant will always remove the same mass of CO_2 from the submarine atmosphere. However it is the ability of the well run plant to achieve this at significantly lower CO_2 concentrations that is the key point.

It is important to note that the MEA solution cannot be stripped of CO_2 merely by heating the solution. The elevated temperature merely results in an increased CO_2 vapour pressure. Unless a steam flow (or other CO_2 -free stripping gas) is present to remove the dissociated CO_2 , the solution will not be stripped.

Scrubber Control

The operator of the scrubber has very little direct control over the performance of his plant. The emphasis is placed on good husbandry rather than direct control. He can alter the setting on the pressure regulator to increase or decrease the operating pressure (temperature) of the regenerators but, as will be seen, this is not always desirable. In the short term, improvement can be made as at the higher temperature CO_2 will dissociate more freely from the solution so improving performance. In the long term however a high temperature will lead to degradation. Therefore, increasing the regeneration pressure cannot be considered as a long-term solution to poor plant performance.

Temperature, pressure and flow are measured at key points in the plant and the operator has to ensure that the scrubber is operated as close to optimum values as possible. Vital clues can often be obtained as to the cause of poor plant performance by close examination of the plant measurements. Even slight deviation from design values can indicate a possible problem. For example in the foam bed scrubber, pressure drop across the porous plates and visual inspection are the only ways of determining whether the foam bed is being generated correctly and hence if sufficient mass transfer area for CO_2 removal is being generated. Small changes in absorber temperature can have a significant effect on CO_2 absorption, since a high temperature solution will reduce the driving force for CO_2 absorption by virtue of its high CO_2 vapour pressure. Regenerator flow rates must also be kept steady to maintain adequate absorber performance, without which MEA will return to the absorber partly saturated, again reducing the driving force for absorption.

To avoid degradation, it is important that the temperature of the amine at any point in the process be kept as low as possible, commensurate with efficient operation of the plant. The operating temperature is highest in the regenerator where the bulk temperature is maintained at 130°C . To maintain this bulk temperature, the local surface temperature on the heater elements

must be significantly higher. In the foam bed scrubber, heating is provided by 27 heater elements wired in three delta groups of nine. Each group comprises three sets of heaters connected in series across each phase. Failure of one element will thus result in the loss of three heaters. The temptation to short out the failed elements must be avoided as such action would result in higher surface temperatures in the remaining two elements, so increasing the rate of degradation.

The most important operator duty, however, is to maintain the MEA solution strength, as measured by titration with sulphuric acid, at its optimum. The solution strength is constantly increasing since the treated air leaves the absorber tower with a higher water content than the inlet air. Although higher strength MEA solutions have an increased absorption capacity for CO₂ they are also more viscous. Increased viscosity reduces the mass transfer coefficient, reducing CO₂ absorption. The latter effect dominates, with the result that increased solution strength reduces CO₂ absorption. With weak MEA solutions the reduced absorption characteristic dominates over the viscosity effect, again resulting in reduced CO₂ absorption. The optimum solution strength is close to 4N (4×normal) which is the recommended operating strength.

Solution Degradation

The U.S. Navy was the first to operate the amine scrubber at sea in the late 1950s. Early problems were encountered which became generally known as degradation. Although the plant would continue to remove the required mass of CO₂, shown by the fact that stable CO₂ levels could be achieved from the atmosphere, it was unable to achieve it at low enough concentration levels. While the background CO₂ level was below the prescribed limit, degradation was of little concern. However, once the level was exceeded the submarine Command was placed in the position of either ventilating or continuing to operate outside prescribed limits.

Aside from the fall-off in scrubber performance, other symptoms of solution degradation were observed. The toxic irritant ammonia was generated as a product of the degradation reaction which caused discomfort to submarine crews. The solution became dark in colour, which interfered with its chemical analysis. Excessive amounts of amine make-up were required to replace degraded solution and excessive foam generation hindered control of the plant.

MEA degradation was a well-known phenomenon within the process industries from which the technology was obtained. The industrial solution to this problem is to simply tap-off a sidestream of the plant charge and replace it with fresh amine. When a sufficient amount of tap-off solution was collected it was batch distilled to separate the useful amine from the spent degradation products. The distilled amine was recycled back to the plant and the spent degradation products dumped as waste.

Such a solution was not a practical proposition for a submarine plant and an alternative solution to the problem was required. An extensive programme was initiated by the U.S. Navy in the 1960s aimed at eliminating or alleviating degradation problems. The American work² concluded that the MEA was being rapidly oxidized by the air, forming degradation products such as ammonia, non-basic nitrogen compounds and peroxides. The hypothesis advanced by research workers was that the oxidation reaction was proceeding mainly in the regenerator where the higher temperature increased the rate of reaction, the oxygen being provided by the MEA which was saturated with respect to oxygen upon leaving the absorber.

In addition, the degradation reaction appeared to be catalysed by the presence of trace quantities of metals, especially copper and iron. Two measures were adopted to combat degradation. Firstly, only stainless steel was used on wetted surfaces of the plant and a small ion exchange column was used to remove metal ions from the fresh water make-up. Secondly, Versine (the monosodium salt of N, N-diethanolglycine*) was added to the solution, which had the dual effect of acting both as antioxidant and as a chelating agent for the metal ions. The chelating effect results from the Versine reacting with the metal ions to neutralize their effects in preference to reacting with the MEA. As a result of this work, all R.N. submarine scrubber fluids now contain Versine. Special efforts are also made to keep the iron concentration low. The scrubber fluid is therefore known as low iron MEA or LIMEA chelate mix, shortened to LCM.

Despite the use of LCM, U.K. submarine scrubbers are still apparently suffering from solution degradation.

Around four years ago, further research work was commissioned by MOD, using shipboard samples of degraded amine from CO₂ scrubbers. Some interesting conclusions were drawn from this work:

- (a) Detection of degraded amine could not easily be related to changes in physical properties. In fact, fairly sophisticated analysis techniques were required to identify degraded solutions.
- (b) Solution colour was not an accurate indication of solution degradation. Several samples of dark scrubber fluid proved to have satisfactory CO₂ absorption and stripping characteristics.
- (c) CO₂ absorption and stripping characteristics of degraded samples appeared to have characteristics comparable to those of fresh solutions.

These results tend to contradict the hitherto accepted premise that a dark MEA solution was an indication that the solution was degraded and that it was no longer capable of absorbing CO₂. This is clearly not the case. Industrial amine plant experience through the years has shown that, provided the products of degradation do not alter the physical properties of the MEA solution (especially the viscosity), then the CO₂ absorption/stripping characteristics of the solution are not impaired.

Effective solution clean-up then becomes of prime importance in preventing the build-up of unwanted degradation products in the solution. Commercial experience has shown that carbon filters are extremely efficient in removing unwanted degradation products. The new MPT scrubbers, soon to be introduced in SSN 17, have carbon filters installed in the MEA circuit. Current scrubbers have only cartridge type filters installed in the MEA circuit. MOD is preparing a trial to evaluate the benefits of installing a new carbon filter in place of the cartridge filter.

Other lessons can be learned from industrial operations. The effect of temperature on degradation reaction rate is well documented. Excessively high regenerator temperatures are known to accelerate the reaction rate and for this reason scrubber regenerators should be operated at low rather than high temperatures. This means that the operator should resist the temptation to increase the regenerator operating pressure, since any short-term improvement in plant performance will inevitably result in degradation of the solution leading to increased operation problems in due course.

In the longer term MOD is preparing to evaluate the use of alternative non-degrading CO₂ solvents which would replace MEA altogether and eliminate the problem of MEA toxicity and degradation. One promising alternative

*'N,N-' refers to the orientation of the ethanol groups in the molecular structure, 'N' indicating a linear carbon chain as opposed to 'iso' indicating a branched chain.

soon to be evaluated is a solvent called Alkazid which is used in commercial CO₂ removal processes.

Since actual operating conditions can never be satisfactorily simulated in land-based trials plant, on occasions when solution degradation occurs at sea the opportunity should be taken to provide useful and valuable information to technical support units at Foxhill. Operators should try to ensure that a full set of plant readings and visual observations accompany any claim that solution degradation has occurred in the scrubber. This information can then be used to simulate process conditions more accurately in a land-based unit in order to gain a better understanding of the degradation phenomenon.

Installation Problems

For any air purification equipment to operate effectively it must interface adequately with the submarine's ventilation system. This is especially so with the MEA scrubber. No matter how efficient the plant, unless CO₂-rich air is directed into the plant at the required rate it cannot maintain acceptable CO₂ levels. Installation problems have been experienced due to poor integration of the scrubbers with the ventilation system. In one instance air tended to circulate around the plant, purified air being drawn back into the inlet in preference to foul air from the remainder of the submarine. This was often overcome by 'jury rigging' temporary vent trunking to direct air from the main exhaust directly into the plant.

In another instance, a defect on a main exhaust fan caused total air circulation rates around the submarine to fall. This had the knock-on effect that less CO₂ was presented to the scrubber for removal and so atmospheric levels rose.

Through the life of a submarine there is a general tendency for the complement to rise. Hence the load on the scrubbers increases. Fortunately the process is such that, as already described, when the background concentration of CO₂ rises, so does the mass of CO₂ it will remove. This means that for an enhanced complement a new equilibrium level can be achieved. However, as that equilibrium level rises so it approaches the MPC₉₀. In older classes of submarine there is little reserve between the equilibrium level and prescribed limit, so any defect causing a fall in performance can push the atmospheric concentration over the limit.

TABLE II—Performance of Foam bed and MPT Scrubber Plants

	<i>Foam Bed</i>	<i>MEA Packed Tower</i>
CO ₂ removal capacity at 1% CO ₂ background	1.7 m ³ /hr	4.2 m ³ /hr
Air treatment flow	520 m ³ /hr	628 m ³ /hr
Absorber MEA flow rate	9 l/min	105 l/min
Regenerator MEA flow rate	2.27 l/min	4.9 l/min
Size	1.7 m × 1.3 m × 1.68 m	1.75 m × 1.3 m × 1.22 m
Volume	3.7 m ³	2.77 m ³
Weight	2794 kg	1723 kg
Power Consumption	18.7 kW	18 kW

Present Work

SSN17 and onwards will be fitted with the MEA packed Tower or MPT scrubber. As the name implies, the significant feature of the plant is the packed absorption tower, which performs the task of the foam bed in the earlier plant. The absorption tower consists simply of a cylindrical vessel packed with a spiral wound, woven wire mesh (FIG. 6). Foul air and lean MEA are passed down through the tower, the mesh providing a large surface area for contact between the air and MEA for efficient absorption of CO_2 .

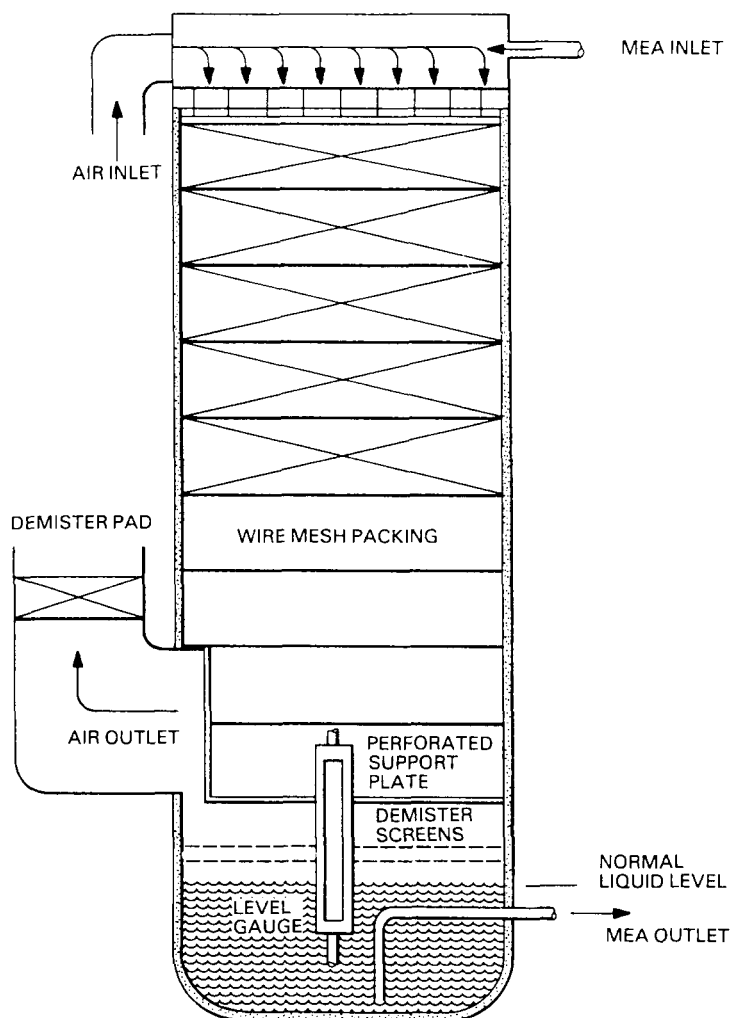


FIG. 6—ABSORPTION TOWER OF MPT SCRUBBER

The relative performance of the foam bed and MPT scrubbers is shown in TABLE II (on p. 541). The significantly higher performance of the MPT can clearly be seen, as can the variation of certain process parameters, notably the absorber flow rate. It was originally assumed that the increase in performance was due entirely to the packing and increased flow rate in the absorption tower, as the regenerator bears a close resemblance to the foam bed unit. Closer examination however revealed that this was not the case and that the possibility existed for uprating foam bed plant by changing certain operating parameters. It was therefore decided to investigate the feasibility of uprating the foam bed plant to achieve improvements in CO_2 control in older submarines without resort of backfit of the MPT.

Numerous ideas and modifications were proposed. The problem then became one of deciding which were likely to give the best return in terms of increased CO₂ removal capacity. In the absence of a readily available trials unit, a computer model of the Mk.6 scrubber was developed which could quickly assess the affects of changes to the design and operating conditions of the plant.

Close examination of the design of the new MPT CO₂ scrubber, which has nearly double the CO₂ removal capacity of existing foam bed units for a similar size unit and power consumption, revealed certain other features which could usefully be incorporated into the existing foam bed units. Once again the computer model proved to be a useful and speedy method of identifying 'best bet' modifications more easily.

Among the improvements identified for further trials work are:

- (a) Increase regenerator flow rate to 4.54 l/min by replacing the existing pump pulley with one of a smaller diameter. The effect of increasing regenerator flow rate is to produce an overall leaner MEA entering the absorber. This in turn increases the driving force in the absorber resulting in lower background CO₂ levels.
- (b) Replace existing regenerator packing with a smaller more efficient random packing. Changing the packing will increase the surface area in the regenerator and will, therefore, increase the quantity of CO₂ stripped from the amine. This in turn will result in a leaner amine entering the absorber thereby lowering the CO₂ background level.
- (c) Replace the existing tubular MEA/MEA heat exchanger with a more efficient plate exchanger. This will increase the degree of heat exchange between the rich and lean MEA streams resulting in a higher inlet temperature to the regenerator. This in turn will increase the quantity of stripping steam produced and will result in a leaner amine being produced. As before, this will lower the CO₂ background level.
- (d) Relocate the MEA/chilled water cooler on the discharge side of the absorber pump. MEA in the absorber sump is at approximately submarine ambient temperature since it is heated by the inlet air entering the absorber. Using an improved MEA/MEA heat exchanger, the lean solution returning from the regenerator will be approaching the current absorber operating temperature before it enters the chilled water cooler. This cooler can therefore be used to cool all of the MEA entering the absorber so reducing its overall operating temperature. Reducing the operating temperature reduces the equilibrium CO₂ partial pressure in the absorber and hence increases the driving force. An increased driving force results in a lower CO₂ background level being achieved.
- (e) Install additional woven mesh packing on top of absorber porous plates and relocate MEA spray bars. This modification will increase the surface area available for mass transfer and will also convert the absorber operation from co-current to the more efficient counter-current mode. A combination of increased driving forces and increased surface area will result in a lower CO₂ background level.

It is estimated that the result of installing all these modifications in the Mk.6 Scrubber could reduce the CO₂ background level for a plant currently maintaining 1% to around 0.6%.

It has been recognized for some time that a reliable measurement of lean and rich MEA concentrations is of paramount importance in determining the efficiency of the absorber and the regenerators. The current analytical method is inaccurate and lacks reproducibility and has now been abandoned. This means that scrubber operators are unable to determine whether the

problem lies in the regenerator or the absorber. A new analytical method has been developed which promises to be a major improvement over the old method. The apparatus is undergoing field trials and will be supplied to the fleet if it is proved reliable.

Future Work

It is expected shortly to commence trials on a land-based foam bed scrubber. The trials will assess the suitability of operating with alternative solvents to MEA. It is also the intention to optimize the process conditions within the plant to maximize CO₂ removal performance. This will involve assessing the effect of changes in flow rate to absorber and regenerator and changes to the operating temperatures and pressures. The modifications identified by the current work will be incorporated into the trials unit and their effect assessed quantitatively. It is also planned to assess the use of a carbon filter in the MEA circulation system to eliminate performance drop-off arising from solution degradation.

If present exposure limits to CO₂ are reduced then in some cases the existing scrubber units will have insufficient capacity to meet the increased CO₂ removal demand. Replacement with a completely new plant is unlikely to be acceptable on economic grounds and therefore uprating of existing units by carrying out minor modifications and optimizing process operating conditions is the only realistic alternative. The trials work planned will provide very useful data and information to enable uprating to be carried out in a logical and effective manner.

Whether we love them or hate them, MEA scrubbers are going to be around for a long time to come. Hopefully, when trials and development work are completed there will be a lot more information available on how best to operate and design scrubbers and many of the perennial problems such as solution degradation will be solved. Certainly, future developments promise much improved units. Only time will tell if they are achievable.

References

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