

# LIQUID OXYGEN PLANTS IN THE 'INVINCIBLE' CLASS

BY

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## Introduction

The LOX plant is an essential part of the INVINCIBLE Class weapon systems. No LOX means restricted Sea Harrier operations.

During the last 25 years, oxygen for R.N. pilot respiration has been supplied from installed converter packs filled with liquid oxygen (LOX). The volumetric expansion of LOX into the gaseous form (i.e. 840 to 1) gave the pilot sufficient oxygen for a sortie of several hours' duration. In order to sustain flying operations on a world-wide basis LOX has to be produced and stored within the aircraft carrier since its natural volatility precludes its handling and transit by the normal stores network. However if you happen to be serving in the INVINCIBLE Class of carrier you will soon be indoctrinated in the poor performance and reliability of the existing LOX plant and their immediate effects on air operations. Such is the debate that rumours have been rife of the possibility of scrapping the LOX plant altogether and replacing it with a modern, more reliable GOX (gaseous oxygen) plant. It is unfortunate that the LOX plant has been bedevilled with a number of circumstances which have undeniably given it a poor reputation. This article clarifies some of the issues surrounding this much maligned equipment and outlines the measures taken by the Procurement Executive to improve oxygen facilities in the 1990s.

## Liquefaction of Air

### *By Expansion and Heat Exchange alone*

In order to understand the method of obtaining liquid oxygen, it is necessary first to consider the process of air liquefaction.

The principles of a simple liquid air plant are shown diagrammatically in FIG. 1 which represents the fundamental high pressure liquefaction cycle. Gas is expanded from 207 bar (3000 p.s.i.a.) to 1.5 bar (22 p.s.i.a.) and to some lower temperature. The flow through the plant is, of course, continuous, but for purposes of explanation it is convenient to consider the 1st, 2nd, 3rd, etc. kilogram of air put out from the air compressor. When the first kilogram of air passes down the high-pressure coil of

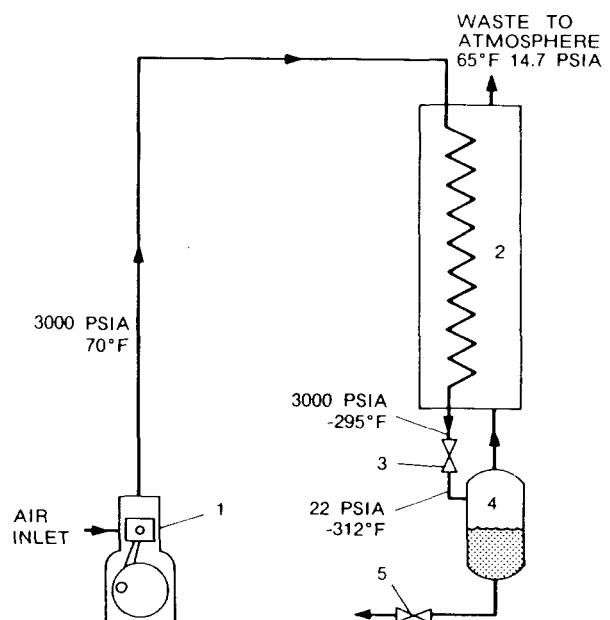


FIG. 1—AIR LIQUEFACTION BY EXPANSION

- 1: multi-stage air compressor
- 2: heat exchanger
- 3: expansion valve
- 4: phase separator
- 5: product outlet valve

the counterflow heat exchanger no change in temperature occurs for there is no return flow on the low pressure (shell) side with which it can exchange any heat. As the first kilogram blows through the expansion valve, its temperature falls a little. The gas then flows into the flash tank or liquid receiver and passes up the low pressure (shell) side of the counter-flow heat exchanger. The drain valve on the flash tank is closed at this time.

If the second kilogram of air at high pressure is just starting down the heat exchanger coil as the first kilogram is going up the shell, these two kilograms will be in thermal contact. The first kilogram will be warmed and the second cooled. As a result, the second kilogram will arrive at the inlet of the expansion valve at a somewhat lower temperature than did the first. The second kilogram will expand, and at the end of the expansion it will be cooler than was the first kilogram after it had expanded.

The second kilogram will now proceed up the shell of the exchanger, and cool the third one which will be cooler still after its own expansion. The process goes on and on, the plant gradually cooling down and the inlet gas to the expansion valve reaching quite low temperatures. Eventually the blow-down through the expansion valve will carry the air into what is known as the two phase region. This means simply that the discharge from the valve contains both liquid and vapour and not just a single gaseous phase. The liquid fraction will begin to accumulate in the bottom of the flash tank, where it can be withdrawn through the product drain valve.

Possible values of temperature and pressure are indicated in FIG. 1 and the theoretical liquid yield of such a plant would be 9%. Since the available refrigeration not only has to cool and condense the air, but also to cool down the metal of the plant itself and to keep it cool, the counterflow heat exchanger, expansion valve, liquid receiver and associated piping must be heavily insulated to reduce the heat leakage from the surrounding atmosphere into the low temperature parts of the plant. If the insulation were not effective, the refrigeration produced would be lost in cooling down the plant and no air would be liquefied at all. The better the insulation, the closer the yield of liquid will approach the theoretical maximum.

#### *With Additional Refrigeration*

In the plant shown in FIG. 1, the refrigeration effect at the expansion valve cools the air from room temperature down to its condensing temperature, and then condenses a fraction of it. The efficiency can be greatly improved by using a Freon\* refrigeration set as shown in FIG. 2 to cool the air to approximately minus 60°C (-76°F) and then letting the Joule-Thomson refrigeration obtained across the expansion valve cool it still further. Theoretically the Freon set is not essential, but as a practical matter it greatly increases the liquid yield of the plant. The cost of power required to drive the auxiliary refrigerator is slight compared to that required to run additional air compressor capacity to give the same yield if the auxiliary refrigerator were not used.

Assuming the auxiliary refrigeration, using Freon as the refrigerant, can cool the air to minus 60°C (-76°F) the plant shown in FIG. 2 would have a theoretical liquid yield of approximately 21% with an inlet air pressure of 207 bar (3000 p.s.i.a.) and expansion down to 1.5 bar (22 p.s.i.a.). The main counterflow heat exchanger has been divided into two parts. Between the first and second parts, the high pressure air stream is taken into a Freon evaporator in which the air passes through coils and the Freon passes through the shell. After the air has been cooled by the evaporating Freon it is

\*Freon is a registered trade mark.

delivered to the second part of the counterflow heat exchanger in which it is cooled further before it enters the expansion valve.

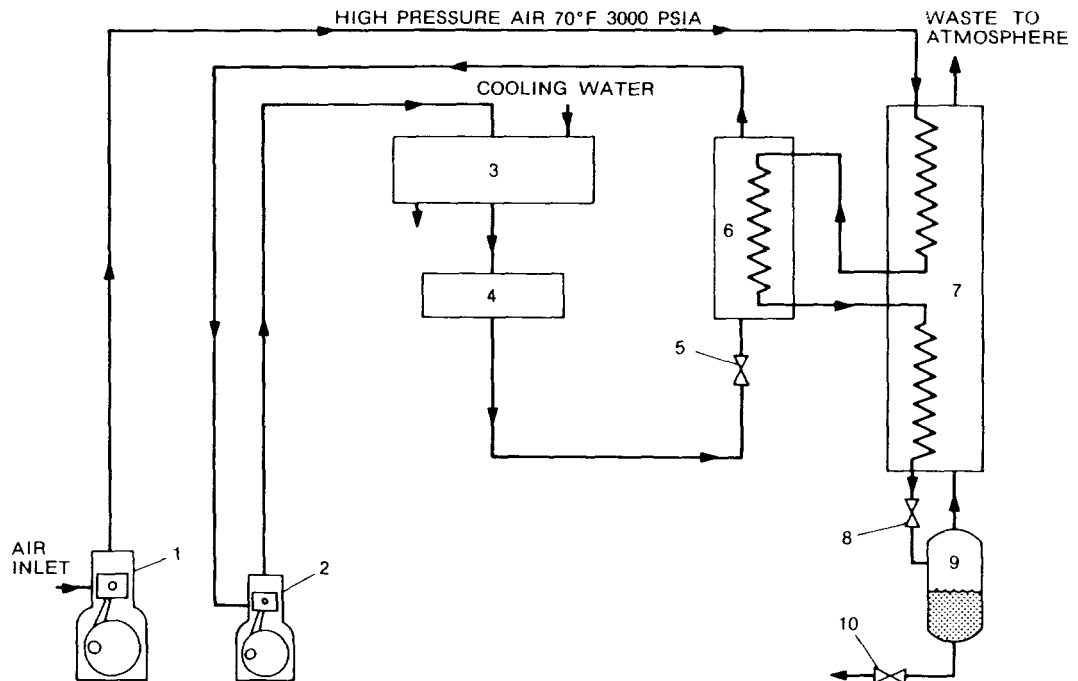


FIG. 2—AIR LIQUEFACTION BY EXPANSION AND REFRIGERATION

- 1: multi-stage air compressor
- 2: Freon compressor
- 3: Freon condenser
- 4: Freon liquid receiver
- 5: Freon expansion valve
- 6: Freon evaporator
- 7: main heat exchanger
- 8: air expansion valve
- 9: phase separator
- 10: product outlet valve

### Removal of Impurities from the Air

In any air liquefying plant (often known as a cryogenic plant), the high pressure air stream is cooled to temperatures so low that if there is any water vapour in this air it will freeze out as water ice or snow and any carbon dioxide will solidify to carbon dioxide ice. If no action is taken to remove the water vapour and carbon dioxide they will eventually block the piping and heat exchangers. As much water as possible is removed by condensate traps in the intercoolers and aftercooler of the air compressor, but there is a certain amount which cannot be removed in this way and which must be removed by other means.

In the kinds of plant described above it is standard practice to use duplex activated alumina filled driers to remove water vapour, and duplex silica gel filled carbon dioxide filters or adsorbers to remove carbon dioxide from the high pressure air. These units are located upstream of the heat exchanger and are both two-vessel assemblies, one vessel of each pair being on stream while the other vessel of each pair is being cleaned. This system is cumbersome as it necessitates additional piping for the second vessels and also for routing

the defrosting and drying gas through them. This defrosting and drying gas further has to be provided with a reactivation heater and blower.

In more modern plants, operating at lower pressures, specially designed reversing flow plate fin heat exchangers are used. In this system, water vapour and carbon dioxide are frozen out of the air and deposited in the heat exchanger. The deposits are subsequently removed by out-going waste gas when the exchanger flow is reversed, the reversal being effected by a fully automatic controller at regular predetermined intervals. It will readily be seen that this system will be far more economic than the previous plants in instances where large volumes of product are required.

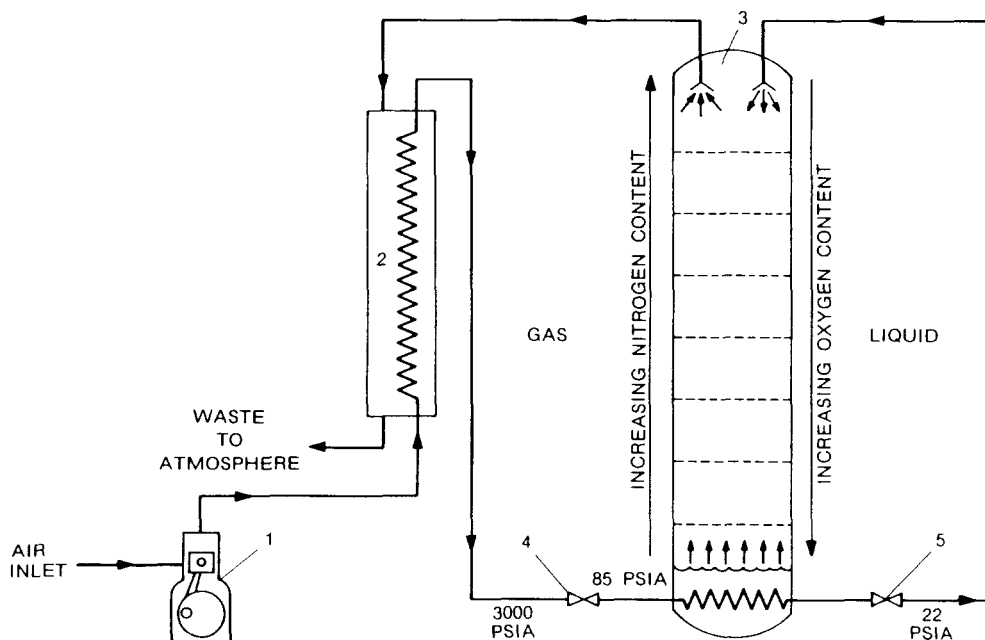


FIG. 3—REFLUX DISTILLATION COLUMN FOR OXYGEN SEPARATION

- 1: multi-stage air compressor
- 2: heat exchanger
- 3: distillation column
- 4: 1st expansion valve
- 5: 2nd expansion valve

### The Separation of Oxygen

In the theoretical plants above, the end product is liquid air. The separation of nitrogen and oxygen from the liquid air is achieved by incorporating a reflux distillation column as shown in FIG. 3. The combined assembly of air drier, carbon dioxide adsorber, Freon air cooler, and distillation column is known as an Air Separation Unit (ASU). The equipment includes a distillation column comprising a tower with a coil in a well at the bottom and, above that, tiers of perforated trays. Vapour rises from tray to tray and liquid falls from tray to tray, collecting in the well at the bottom. As the liquid falls it becomes more and more rich in oxygen content, and as the vapour rises it becomes richer in nitrogen. The bottom (oxygen) end of the column is the warm end. There is a temperature variation along the length of the column, but pressure is constant. Based on the principles of FIGS. 1 to 3,

the basic shipborne plant is shown schematically in FIG. 4. In practice a single distillation column would be several metres high. For ship use, the column is split into three columns each about 2.5 metres high.

The LOX is drawn off at a temperature of  $-182^{\circ}\text{C}$  ( $-297^{\circ}\text{F}$ ) and transferred to storage tanks which are vacuum-insulated to reduce evaporation losses. The product is then routed to the LOX charging bench where four converter packs are filled simultaneously. Once filled, the converter packs are then installed in the aircraft for operational use. A small amount of GOX is produced by vapourizing the LOX in a heat exchanger contained in the ASU. The GOX is stored in bottles up to 3000 p.s.i.

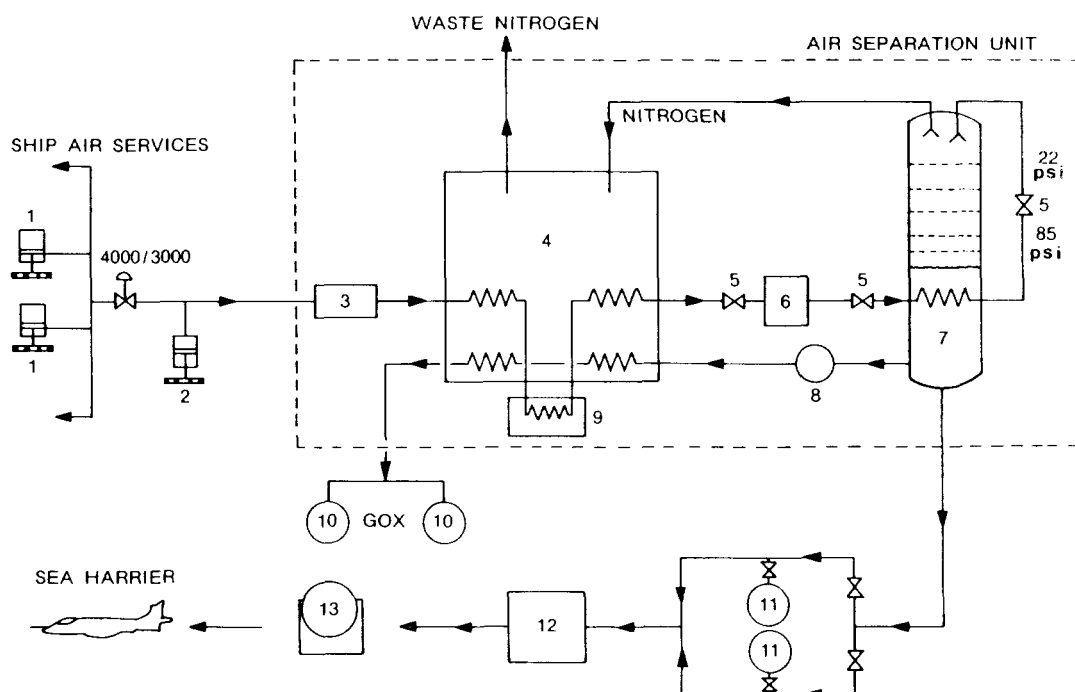


FIG. 4—Schematic arrangement of shipborne LOX plant

- 1: Reavell R80 HPAC
- 2: Reavell TC6 Mk.3A HPAC
- 3: air drier
- 4: heat exchanger
- 5: expansion valve
- 6: carbon dioxide adsorber
- 7: distillation column
- 8: LOX pump
- 9: Freon plant air cooler
- 10: GOX storage bottle
- 11: LOX storage tank
- 12: LOX charging bench
- 13: LOX converter pack

### LOX Plants since 1959

The LOX plant Air Separation Unit in use today<sup>1</sup> (Type RS 500) first entered service in the early 1960s when they were fitted in H.M.S. *Ark Royal*, *Eagle*, and *Hermes*, to support the Buccaneer and Phantom aircraft. The plants were heavily used and gave reasonable performance and reliability. Development of the plant was axed in the 1970s when it appeared that carrier-borne fixed wing flying would be phased out.

The decision at relatively short notice to embark five Sea Harriers in the INVINCIBLE Class posed the Ship Department at Bath a problem over the

supply of LOX. It was decided in 1977 to fit *Invincible* with a single RS 500 LOX plant ex H.M.S. *Eagle*. The plant, which was already about 17 years old, had to be sent to Vickers Shipbuilding and Engineering Ltd (VSEL) for refurbishment. The individual main assemblies, e.g. air compressors, Freon plants, LOX charging bench, Air Separation Unit, etc., were each sent to the parent manufacturer for refurbishment and modernization before being commissioned in *Invincible*. Unfortunately the exact details of the state of refurbishment were not properly recorded and hence comprehensive revised drawings were not issued. Despite its age, the plant was destined for several more years' service without any redundancy. The follow-on aircraft carriers, H.M.S. *Illustrious* and *Ark Royal* were again fitted with a single but new RS 500 LOX plant. In both instances the design was essentially the same but incorporated a number of minor modifications to overcome the obsolescence of the *Invincible* plant.

### Current In-service Problems

The main problems encountered with the RS 500 plant can be grouped broadly into the following categories:

- (a) Inadequate air supply arrangements.
- (b) Poor spares and technical support.
- (c) No redundancy.

#### *Air Supply Arrangements:*

In order to produce 99.5 per cent. pure LOX at rated output, a stable air supply to the Air Separation Unit (ASU) is required under all temperature conditions. The demand for air in the ASU will always rise to compensate for leaks and lower air densities in tropical climates. The dedicated LOX HP air compressor, however is a Reavell TC6 Mk. 3A which has a maximum output only a little above the normal requirement of the ASU; hence any shortfall in compressor performance aggravated by an increased ASU demand will cause a marked deterioration in LOX output. Air supplies can, however, be drawn or supplemented from the ship's general service air ring main (see Fig. 4). Unfortunately the ring main is itself supplied by only two Reavell TC R80 HP air compressors. In the event of one compressor failure, the remaining compressor cannot always maintain a steady ring main pressure of 275 bar (4000 p.s.i.a.) when the demand is heavy, i.e. during diesel and gas turbine starting. The 275 bar/205 bar (4000/3000 p.s.i.a.) pressure reducer is sensitive to fluctuating input air pressures and hence the output of air to the ASU will be erratic, with consequent deterioration of LOX quality and quantity.

In warm climates the evaporation losses of LOX in the storage tanks and associated pipework increase dramatically because of the limitations of the vacuum insulation. When LOX is transferred from a tank to the charging bench all metal in contact with the oxygen has to cool down to  $-182^{\circ}\text{C}$  ( $-297^{\circ}\text{F}$ ) before the oxygen will remain in the liquid phase in the converter pack. Thus up to 8 litres of LOX are used for every litre transferred into the converter pack. Such losses can be quite intolerable if the ASU LOX output is limited by fluctuations in inlet air supplies.

#### *Technical and Spares Support*

The refurbishment of the LOX plant ASU for *Invincible* posed an immense task for the manufacturer. The plant had been considered to be out of date and few of the original manufacturing drawings were held. A search amongst the archives of Foxhill revealed some that were still applicable and which therefore became very useful in the rebuild of the plant. Old pipework and

obsolete valves were replaced but a revised set of drawings reflecting the revised ASU arrangement was not produced. This in turn meant that an Illustrated Parts Catalogue (IPC) and an associated Provisioning Schedule could not be produced and hence SPDC Eaglescliffe could not purchase spare parts. Furthermore the absence of drawings meant that the B.R. could not be comprehensive. The ASU was, however, practically the same as that fitted in *Illustrious* and *Ark Royal*, where a full set of manufacturer's drawings was available. It was unfortunate that the opportunity was not taken to use these drawings as a basis for the technical publications of all three ships.

### *Redundancy*

The decision to provide only one LOX plant obviously imposes immense difficulties in the event of system failure. The LOX tanks can sustain several days' flying operations normally, but this is not always the case in tropical climates where the effects of low air density and high evaporation losses aggravate the situation. The maintainer is under pressure to restore equipment performance as soon as possible and that is no easy task when spares are not always available.

### **The Way Ahead**

The problems associated with LOX are well recognized by MOD(PE) and several activities are in progress to improve the situation.

#### *Short Term*

In the short term the following actions have been taken or are in hand:

- (a) Supply of manufacturers' drawings (applicable to the RS 500 plants in *Illustrious* and *Ark Royal*) to all three ships of the class: completed April 1985.
- (b) Supply of emergency spare parts kits direct from the manufacturer: due in December 1985.
- (c) Provision of an Illustrated Parts Catalogue for the LOX plant ASU, using drawings applicable to *Illustrious* and *Ark Royal*: expected late 1986.
- (d) Revision of the existing BR 6555 (001) for *Invincible*: due 1986.
- (e) Provision of a separate BR for *Illustrious* and *Ark Royal*: expected 1986.

#### *Longer Term*

Bearing in mind that all three carriers will be operational for at least another 20 years, there is strong pressure to replace the 26-year-old design of LOX plant. Furthermore, from 1986 onwards, the Sea Harriers will start using GOX packs (charged to 345 bar, 5000 p.s.i.a.) which can be interchanged directly with the LOX packs. GOX is produced by making LOX as an intermediate product, the same amount of oxygen being stored in far less space as LOX. The LOX plant system must be capable of producing and storing large quantities of LOX/GOX so that the amount in store can provide a buffer against the effects of having no plant redundancy.

There are two options to pursue:

- (a) Modernize the existing plant, with an enhanced GOX making facility.
- (b) Design, build, and fit a new LOX/GOX plant.

Three companies have been selected to undertake feasibility studies into both options. The following aspects will be considered in each study:

- (a) Improved air supply and metering arrangements.
- (b) Increased stored LOX capacity.
- (c) Plant to be automatic or semi-automatic.
- (d) Reduced evaporation losses.
- (e) Duplex arrangements for all pumps and intensifiers.
- (f) LOX pump to take suction from the ASU and from the storage tanks.
- (g) Enhanced GOX making facility.

If it is decided that a replacement or improved plant is operationally required, then one of the three contractors will be awarded a contract for a detailed design.

Since major improvements can only be undertaken during refits, it will be many years before all three ships are converted. As the Sea Harrier will soon be operating on GOX, an interim measure must be taken in order to ensure that the ships can charge GOX packs up to 5000 p.s.i. before their refits. A GOX intensifier (often known as a booster unit) will be installed. This will be able to boost the pressure of the stored GOX in the existing plant up to the pressures required by the converter pack. The intensifiers are undergoing shock, vibration, and performance, trials, and will be available in 1986.

#### **Acknowledgement**

The section on the theory of air liquefaction is based on a publication by Air Products, Ltd.

#### *Reference*

1. Robinson, C. M.: Liquid oxygen (LOX); *Journal of Naval Engineering*, vol. 15, no. 1, June 1964, pp. 67-75.
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