

# Hollow Fiber Membrane Gas Separation for Ground-Based Inerting

## Objective

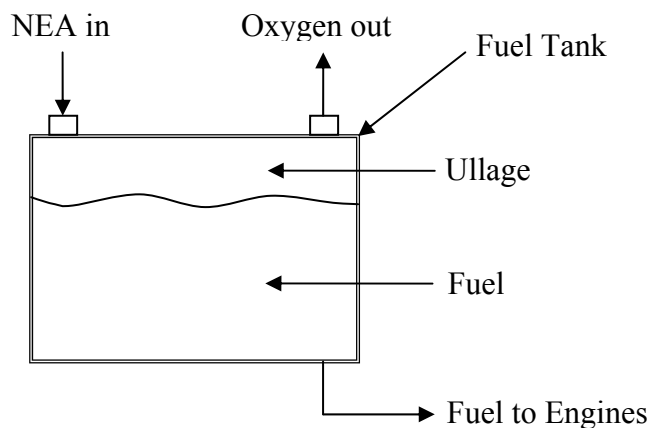
The objective of this experiment is to design a hollow fiber membrane gas separation system for the ground-based inerting of aircraft.

## Introduction

On July 17, 1996 TWA Flight 800 exploded after take-off from New York's JFK Airport and plunged into the Atlantic Ocean just south of Long Island. The Paris-bound 747 carried 230 passengers and crew members that died as a result of the accident. While the explosion was initially blamed on a missile fired by a U.S. Navy ship, a National Transportation Safety Board (NTSB) investigation [1] concluded the explosion probably resulted from a spark that ignited vapors in the center wing fuel tank (CWT) – a living room sized metal box.

This accident, along with numerous others blamed on fuel tank explosions [2], spurred the Federal Aviation Administration (FAA) to investigate technologies that could reduce or potentially eliminate fuel flammability concerns [3]. One such technology is ground-based inerting (GBI). GBI involves displacing the vapor headspace (initially containing 21% oxygen after refueling) above the liquid fuel with nitrogen enriched air (NEA, containing 1-5% oxygen). As illustrated in Figure 1, NEA is forced into the vapor headspace to displace the air initially present there. This headspace, referred to as the ullage, depends on the fuel tank size and loading. Additionally, the ullage will change during flight as fuel is removed for combustion in the engines.

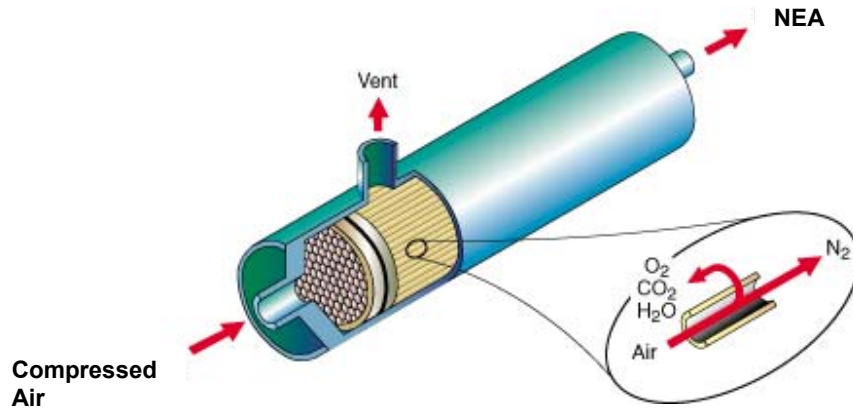
Figure 1. Displacement of air in the ullage during ground based inerting.



One process under consideration for producing the NEA uses hollow fiber membrane gas separation technology. In the process, compressed air is fed to a hollow fiber gas separation module. The module consists of a bundle of hollow fibers enclosed in a case. Each fiber is approximately 200-400 microns in outer diameter and 100-300 microns inner diameter. The wall of the fiber is more permeable to oxygen than nitrogen so as air flows through the fiber lumen oxygen is removed and an enriched nitrogen stream is left behind. The case possesses two

external ports on either end of the fiber bundle, and two ports along the periphery of the case. The latter two ports allow the unit to be run in counter-current or co-current mode, depending on which valves are opened. A module with a single port along the periphery is illustrated in Figure 2.

Figure 2. Hollow fiber membrane gas separation module in operation.



Commercially available modules can produce NEA at various flow rates and purities. Modules are characterized by determining the product flow rate as a function of nitrogen purity. Additionally, the fraction of the feed air that is recovered as NEA product is determined. The ratio of product to feed flow rate, called the recovery, determines what compressor size is required to provide compressed air to the module.

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**Work Statement**

You have been asked to evaluate the number of modules, feed air requirements, and compression requirements to inert the combined fuel tank ullage of a generic aircraft. Fuel tank volumes for various generic aircraft are given in Table 1.

Table1. Generic aircraft fuel tank sizes.

<i>Aircraft Type</i>	<i>CWT Volume (Gal.)</i>	<i>CWT + Wing (Gal.)</i>	<i>CWT + Wing + Aux (Gal.)</i>
Business Jet	N/A	6,273	N/A
Small	3,060	5,100	7,600
Medium	10,200	24,480	27,480
Large	25,500	55,080	58,080

For each plane type, the center wing fuel tank volume is provided as well as additional fuel tank volumes in the left and right wings (Wing) as well as any auxiliary fuel tanks (Aux). Past work

[4] has shown that one can calculate the oxygen concentration in the ullage as a function of time after initiating the NEA purge from the following equation,

$$(1) \quad \frac{y_A - y_U(t)}{y_A - y_{NEA}} = 1 - \exp\left(-\frac{Qt}{V}\right)$$

where  $y$  is the oxygen mole fraction, the subscript  $A$  indicates the value for ambient conditions (i.e., 0.21), the subscript  $U$  indicates the value in the ullage, the subscript  $NEA$  indicates the NEA stream,  $Q$  is the NEA volumetric flow rate,  $V$  is the ullage volume, and  $t$  is elapsed time since starting the NEA purge. The mole fraction ratio on the left of Equation (1) is referred to as the “inerting ratio” while the ratio in the exp function on the right is referred to as the “volumetric tank exchange” (VTE). The VTE indicates how many times the ullage volume has been displaced by NEA.

You are to calculate the NEA composition and flow rate to inert the combined fuel tank ullage of a generic aircraft using NEA. The tank is considered inerted when the oxygen concentration drops below 8%. You may assume aircraft operate with fuel loadings of 60-90%. Additionally, the time available to inert the tank is limited by aircraft turnaround times – the time between when an aircraft arrives at the gate and the time it leaves for its next destination. Inerting must be completed on or before the allotted turnaround time has elapsed. Typical turnaround times are given in Table 2.

Table 2. Typical turnaround times for generic aircraft.

<i>Aircraft Type</i>	<i>Turnaround Time (min)</i>
Business Jet	65
Small	25
Medium	50
Large	65

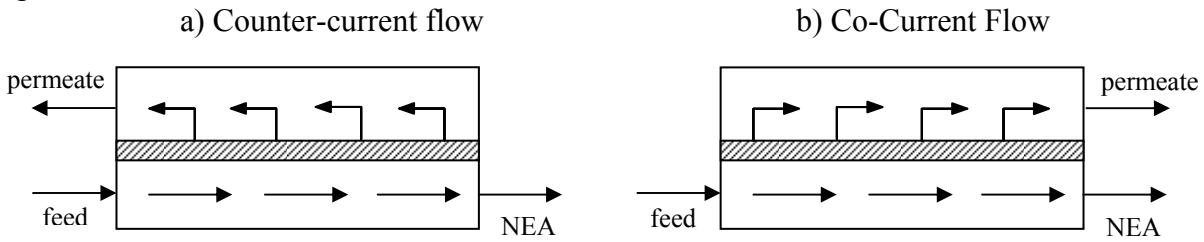
Additionally, you are to determine the number of hollow fiber gas separation modules required to provide the NEA and to size a compressor to provide the required NEA flow rate. A sample module has been provided for your testing to obtain the data required to do this.

## Theory

Polymeric membranes in the form of sheets or fine hollow fibers can be used to separate gas and liquid mixtures due to differences in permeation rates through the material. This makes membrane process very useful for a wide range of separations. In this experiment, oxygen permeates through the material faster than nitrogen, due to higher solubility and diffusivity in the polymer, so one can produce a nitrogen-enriched and an oxygen-enriched stream with a membrane process.

The separator in this experiment can be run in two different modes: counter-current flow and co-current flow. These two modes are pictured in Figure 3.

Figure 3. Counter-current and Co-current Flows.



When deriving mathematical models of a gas separations unit, concentration gradients normal to the surface of the membrane are considered negligible. This is justifiable because, unlike liquids, gases form little or no boundary layer along a surface when it flows past. Therefore, the resistance of the boundary layer relative to that of the membrane itself is very small and a concentration gradient does not occur. On the other hand, there is a significant concentration gradient as the gas moves from one end of the unit to the other because oxygen is constantly being removed. How one accounts for this concentration gradients leads to different mathematical models of module performance.

### Complete-Mixing Model

This model is based on the assumption that there is little or no concentration gradient within the permeated gas axially along the fibers. Therefore, this case simplifies to a simple mass balance of the oxygen within the unit. Equations for  $x_o$  and  $y_p$  can be derived from a component mass balance on oxygen and an overall balance.

Equation 2 can be used to calculate the fraction of the feed that is recovered as NEA [5]:

$$(2) \quad \frac{q_o}{q_f} = 1 - \theta = 1 - \frac{A_m (P'_{O_2} / t) (p_h x_o - p_l y_p)}{q_f y_p}$$

where  $p_h$  is taken to be the same as the inlet pressure and  $p_l$  is taken as atmospheric pressure. See Table 3 for a list of the nomenclature used in equation 2.

### Countercurrent Model

This model is significantly more difficult than the complete-mixing model because it requires the solution of two coupled differential equations. Therefore, a MATLAB program will be provided for your use.

Table 3. Nomenclature.

<i>Symbol</i>	<i>Definition</i>
$A_m$	Surface area of membrane ( $cm^2$ )
$P$	Pressure ( $cm\ Hg$ )
$P'_A$	Permeability of component A in membrane ( $cm^2/s/cm\ Hg$ )
$q$	Flow rate ( $cm^3/s$ )
$t$	Thickness of membrane ( $cm$ )
$x$	Mole fraction of component A in feed or reject
$y$	Mole fraction of component A in permeate
$\alpha$	Separation factor = $(P'_A)/(P'_B)$
$\theta$	Stage cut = $q_p/q_r$
<i>Subscript</i>	
$f$	Inlet feed
$h$	Feed side
$l$	Permeate side
$o$	Reject (NEA) flow
$p$	Permeate flow

## Equipment

This experiment uses a tube fed Permea Model PPA-22AD air separator. Ambient air is fed at ~80 *psig* through two Permea air filters in order to ensure no small particles enter the separator. The necessary specifications for the air separator can be found in table 4.

Table 4. Permea Model PPA-22AD air separator specifications.

Active fiber length	0.533 <i>m</i>
Fiber OD	0.450 <i>mm</i>
Fiber ID	0.350 <i>mm</i>
Oxygen permeance = $P'_{O_2}/t$	8.3E-12 $kg_n/m^2/Pa/s$
Nitrogen permeance = $P'_{N_2}/t$	1.4E-12 $kg_n/m^2/Pa/s$
$\alpha = (P'_{O_2}/t)/(P'_{N_2}/t) = (P'_{O_2})/(P'_{N_2})$	5.9
Number of Fibers	2927

Note that 1 GPU (gas permeating unit) = 3.36E-13  $kg_n/m^2/Pa/s$ .

## Experimental Procedure

This experiment is controlled using National Instruments LabVIEW software. If the control program is not running, contact the laboratory instructor. The instructor will provide assistance in learning how to run the experiment.

You are to design an experiment with two objectives in mind: 1) You must determine which model best predicts the performance of the Permea PPA-22AD model in both counter-current

and co-current flow. This will require a comparison of experimental measurements of  $\theta$  as a function of NEA concentration to predictions from equation (2) and the provided program. 2) Design a membrane gas separation system for inerting a 747 aircraft (corresponding to a large aircraft in Table 2). You are to specify the required NEA composition, NEA flow rate, feed air flow rate, number of modules, and compressor size (assume compression to the same pressure as used in the lab).

## Laboratory Report

Your laboratory report should be prepared using the guidelines provided by the instructor. Additionally, you should address the following points:

1. Derive Equations (1) and (2).
2. Which operating mode (i.e., counter-current or co-current) is preferred? Why?
3. Which model provides the best prediction of  $\theta$  for counter-current operation? for co-current operation?
4. Provide the following information for your recommended design: NEA composition, NEA flow rate, feed air flow rate, number of modules, and compressor size (assume compression to the same pressure as used in the lab).
5. Would you recommend any changes to the design of the Permea PPA-22AD for use in your application?
6. More than one design is possible. What are the trade-offs for different alternatives?
7. What safety and/or environmental concerns might you have for the use of a membrane process for GBI?

## Literature Cited

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