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AFWAL-TR-88-2031

Advanced Air Separation Module Performance Evaluation

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July 1988

Final report for period May 1986 through September 1987

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Results of an experimental performance evaluation of two advanced light weight permeable membrane (PM) air separation modules (ASM) are presented. ASMs produce nitrogen enriched air (NEA) which is used for airplane fuel tank inerting. The airplane inerting system is termed On-Board Inert Gas Generator System (OBIGGS).

ASMs were obtained from two sources: A/G Technology Corporation and Permea Incorporated. Steady state performance envelope, long term endurance, hot/cold start-up on/off cycling, moisture, vibration, contaminant, and high temperature destructive tests were conducted. Results indicate that a significant breakthrough in OBIGGS weight reduction has been achieved. (continued)

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Both the A/G and Permea ASMs offer significant reductions in weight over present (SOTA) "state-of-the-art" ASM technology.

Performance of the A/G and Permea ASMs is directly compared to other ASM technology in terms of ASM weight as well as total airplane penalties which include bleed air usage and bleed system component weight. Comparisons indicate that the advanced ASMs will allow significant weight reductions in the bleed air system compared to present (SOTA) "state-of-the-art" ASM technology. This was accomplished by using less bleed air at higher temperatures.

Basic ASM performance models are presented along with analysis of ASM moisture sensitivity, pressure drop, and thermal response. Keywords: Fuel tanking inerting systems; Onboard gas generator systems; Inert gas generator systems; Aircraft fire/explosion prevention. (edc)

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SUMMARY

The Air Force is considering the application of On-Board Inert Gas Generation System (OBIGGS) technology to a number of airplanes. Accordingly, OBIGGS that minimize system weight and volume, airplane performance penalties, and logistics penalties are of much interest.

In February 1985, the Air Force requested the Boeing Military Airplane Company assess the potential of new OBIGGS technology as a task under Air Force Contract F33615-84-C-2431. To this end, new ideas and products capable of producing significant improvements in performance over existing OBIGGS systems were solicited during an industry wide survey. The methods used to assess performance potential involved analysis of the Air Separation Modules (ASMs) only and did not consider complete OBIGGS installations. Concepts which promised at least an order of magnitude reduction in size and weight were identified for possible experimental evaluation.

The survey results indicated that advanced Permeable Membrane (PM) technology offered the greatest potential for ASM performance improvement. In particular, A/G Technology had developed, on a small scale, PM hollow fibers that had a high probability of reducing the size and weight of an ASM by at least an order of magnitude. Proposals were solicited in an open competition and A/G Technology was subsequently awarded a contract to provide two ASMs for experimental evaluation in the AFWAL/POSF test facilities located at WPAFB.

A second membrane manufacturer, Permea Inc. later provided an advanced PM ASM on a loan basis. This ASM was of Permea's latest design and was significantly improved over their previous designs.

Both A/G Technology and Permea currently manufacture these membrane based ASMs for use in industrial and commercial applications.

The following tests were conducted to evaluate the performance of A/G Technology and Permea ASMs:

- Performance Envelope
- Performance stability over 2000 operating hours
- Sensitivity to inlet moisture*
- Moisture separation performance*
- Performance during hot and cold start-ups*
- Performance stability over 1000 on/off cycles*
- Sensitivity to vibration*
- ASM vibration response characteristics*
- Sensitivity to inlet air contaminants
- Destructive high temperature test**

Note: * A/G only
** Permea only

The results showed that both the A/G Technology and Permea advanced ASMs provide significant improvements in performance over current ASM technology in a realistic airplane environment. These improvements translate directly into weight savings and reduced bleed air consumption. In fact, the A/G unit achieved an order of magnitude reduction in weight compared to earlier membrane based ASM technology from DOW. The Clifton Precision Molecular Sieve (MS) based ASM represents current technology quite well. However, compared to Clifton MS ASM weights, the A/G unit was about five times lighter and the Permea unit showed a potential of being about two times lighter.

Preliminary estimates of the total system weight (ASM + bleed air conditioning equipment), at the specific conditions chosen for analysis in this report, show that the A/G and Permea systems are essentially equal in terms of total airplane weight penalties. Even though the A/G ASM weighs considerably less than the Permea ASM, total airplane weight penalties are similar because of Permea's lower bleed air system weight penalties.

Higher operating temperatures than those used for the long term endurance tests may be practical for both the A/G and Permea units. In fact, the Permea ASM may be capable of operating at temperatures as high as 250°F. Since new airplane development is oriented to higher temperature environments, tests to evaluate the operating temperature limits of the A/G Technology and Permea ASMs would be of interest.

In any engineering discipline, performance improvements are usually measured in terms of a few percent and it is indeed rare that performance can be increased by a factor of 10. Consequently, the A/G Technology ASM and to a lesser extent the Permea ASM should both be considered technological breakthroughs and truly significant accomplishments.

This experimental program emphasized ASM performance and was not a qualification test of membrane based ASM technology for airplane applications. The next step in membrane based ASM development is to transfer this technology to DoD airplanes. This may be best accomplished by building a flight worthy and fully qualified membrane based ASM for a specific airplane application. Testing should include a realistic ground simulation followed by an actual flight test.

PREFACE

This is a final report of work conducted under F33615-84-C-2431 and submitted by Boeing Advanced Systems (BAS a division of The Boeing Company), Seattle, Washington for the period May 1986 through September 1987. Program sponsorship and guidance were provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSF), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Under Project 3048, Task 07, and Work Unit 94. Robert G. Clodfelter was the project engineer. The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) also provided funds to support this effort.

The work partially satisfies the requirements of Task II, Subtask II-3 of the contract, Fuel System Protection, which requires that the performance of various explosion protection measures be evaluated. This work specifically included advanced air separation technology and its application to various aircraft. Other reports submitted in fulfillment of this contract include:

Document Number	Title
AFWAL-TR-87-2004	Effects of Aircraft Engine Bleed Air Duct Failures on Surrounding Aircraft Structure
AFWAL-TR-87-2060	Development and Evaluation of an Airplane Fuel Tank Ullage Composition Model:
Volume I:	Airplane Fuel Tank Ullage Computer Program
Volume II:	Experimental Determination of Airplane fuel Tank Ullage Composition
AFWAL-TR-87-2089	Optical Fire Detector Testing in the Aircraft Engine Nacelle Fire Test Simulator
AFWAL-TR-88-2031	Advanced Air Separation Module Performance Evaluation
AFWAL-TR-88-(tbd)	Hot Surface Ignition Testing in the Aircraft Engine Nacelle Fire Test Simulator (this document to be released about 1 Oct. 1988)
AFWAL-TR-88-(tbd)	OBIGGS Preliminary Design Studies (this document to be released about 1 Oct. 1988):
Volume I:	A-6 Aircraft
Volume II:	F-18 Aircraft
Volume III:	P-3 Aircraft

Boeing wishes to acknowledge with appreciation the contributions of the technical personnel of Select Tech Services, Inc., who assembled the test set-up and assisted in conducting actual testing.

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1.0 INTRODUCTION

1.1 Background

Unacceptable combat losses due to airplane fires and explosions have prompted extensive studies of a variety of fuel tank explosion protection concepts. As military airplanes become more sophisticated and costly, protecting these valuable assets, as well as improving crew safety, are important considerations. Airplane fuel tanks have been singled out for special attention because a significant percentage of combat airplane fires and explosions are fuel tank related.

Fuel tanks may be currently protected from fire and explosion in several ways:

- o Reticulated foam (A-10, F-15, C-130, F-4, etc.)
- o Halon 1301 inerting (F-16)
- o Nitrogen inerting (C-5A/B, C-17, V-22)

Inerting airplane fuel tanks with nitrogen is a technique that is receiving much attention. Fuel tank inerting consists of reducing the oxygen concentration in the fuel tank vapor space (ullage) to a level which will not support combustion. Based on extensive experimental data, an ullage oxygen concentration of 9 percent has become the accepted criterion to ensure against fuel tank fires and explosions.

Liquid nitrogen (LN_2) fuel tank inerting systems have been installed on the USAF C-5A/B fleet. While the LN_2 system provides the desired level of safety, the use of LN_2 entails a logistics problem. The C-5 LN_2 system has been sized for a maximum of two long range flights after which the system must be refilled from LN_2 ground storage. Only a limited number of bases can provide this service. Airplanes operating from unimproved landing strips could not expect LN_2 to be available.

One proposed solution to the LN_2 logistics problem is to replace the LN_2 system with an On-Board Inert Gas Generator System (OBIGGS) being developed and advocated by the Air Force. During flight, the OBIGGS physically reduces the oxygen concentration of high pressure engine bleed air to safe levels (below

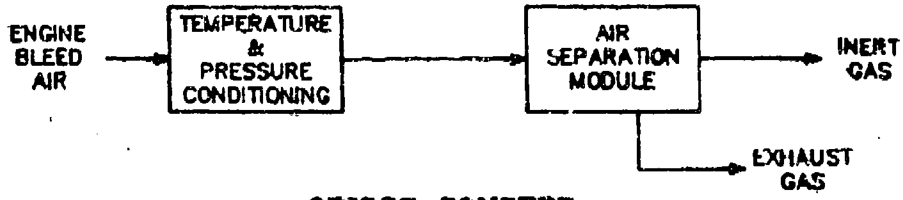
9 percent by volume). The product gas is often termed nitrogen enriched air (NEA); the oxygen rich waste gas from the separation process is expelled overboard or used for other purposes.

Satisfactory performance of the first prototype OBIGGS has been demonstrated by Boeing under a previous Air Force contract by conducting simulated flight tests for a KC-135 (Reference 1). In addition, a complete flight qualified system has been developed for the AH-64A helicopter (Reference 2). The OBIGGS have also been chosen for other airplanes currently being developed (the C-17 and V-22) and is being considered for the ATF.

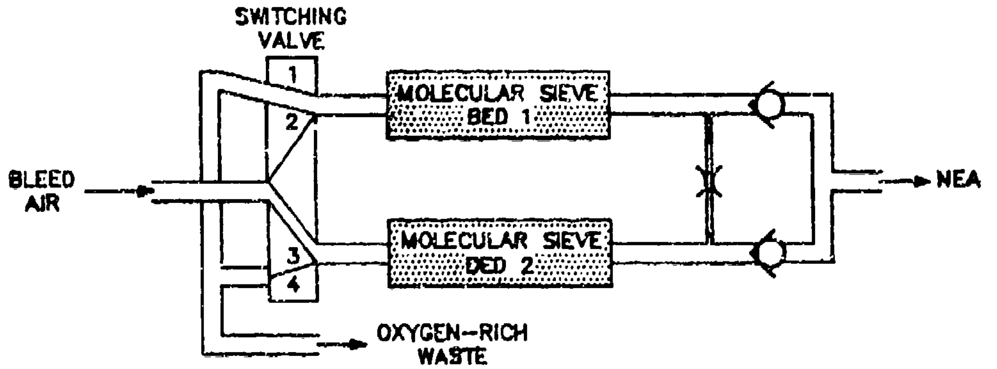
Through about 1985, OBIGGS technology centered around two systems: a Permeable Membrane Inert Gas Generator (PMIGG) manufactured by DOW Chemical (Reference 3,4) and a Molecular Sieve Inert Gas Generator (MSIGG) manufactured by Clifton Precision (Reference 5). Both of these units were experimentally evaluated by the Boeing Military Airplane Company under Air Force Contract F33615-78-C-2063. The results and analyses of these experiments were published in References 1, 6 and 7.

The DOW ASM will be described here due to its similarity to the advanced ASMs currently being developed and the fact that construction details of the advanced units are generally proprietary. A hollow fiber permeable membrane ASM may be constructed with either internally or externally pressurized fibers. As long as a difference in the partial pressure of oxygen exists across the wall of the hollow fiber, selective permeation of the oxygen molecules will occur. DOW has manufactured both types of ASMs but found external pressurization was superior for their particular fibers. However, most advanced membrane development is being based on internally pressurized fibers. For that reason, the construction of an internally pressurized permeable membrane DOW ASM will be described.

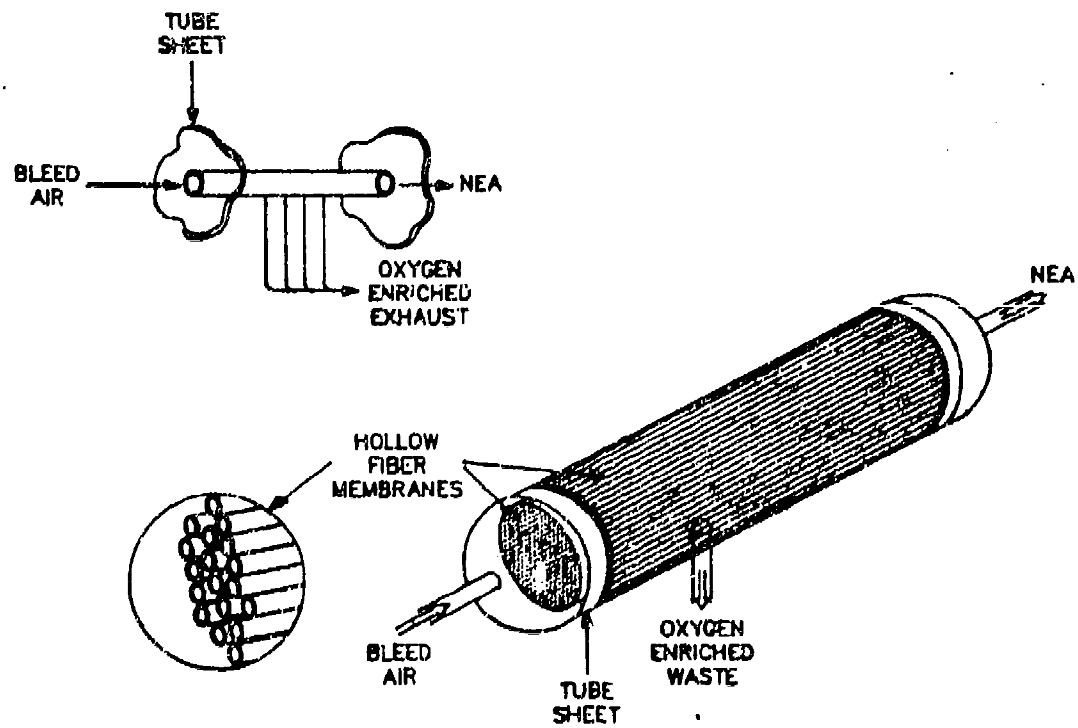
The DOW ASM contains millions of hollow methyl pentene fibers, arranged in a cylindrical bundle (Figure 1). Both ends of the fiber bundle are gathered together at the ends and potted in epoxy tube sheets. After the epoxy cures, it is shaved to open the ends of the hollow fibers. The fiber bundle is then placed in an outer case and connected, as shown in Figure 1. In operation,



OBIGGS CONCEPT



MOLECULAR SIEVE AIR SEPARATION MODULE



PERMEABLE MEMBRANE AIR SEPARATION MODULE

Figure 1. On-Board Insert Gas Generator (OBIGGS)

bleed air is distributed to one tube sheet and into the bore of the individual fibers. As the air flows through the fiber, oxygen preferentially permeates the wall of the fiber so that NEA is produced and collected at the opposite end of the fiber. The NEA is then used to inert the fuel tanks. The oxygen rich gas that permeates the fiber wall is collected and exhausted overboard. The principal control devices are a flow control orifice located in the product stream and an inlet pressure regulator. Note that the permeable membrane ASM is a steady flow system.

The Clifton molecular sieve ASM is based on pressure swing adsorption of oxygen with a minimum of two beds of synthetic zeolite material which are alternately pressurized and then exhausted to ambient (Figure 1). The Clifton ASM is representative of current OBIGGS technology and is the only system currently flying on DoD airplanes. The zeolite material is a Union Carbide 4 Angstrom molecular sieve. At high pressures, oxygen is preferentially adsorbed within the molecular sized pores of the sieve material.

The pressure swing process begins with one bed pressurized, supplying NEA collected from the downstream end of the bed. Simultaneously, the other bed is vented to the atmosphere allowing the oxygen rich gas to be desorbed and vented overboard as waste gas. A small quantity of NEA is used to assist in purging the desorbing bed. The role of the beds alternates in a cyclic process from adsorption to desorption. Clifton Precision has built an eight bed system that was tested by Boeing under Air Force contract (Reference 1,5). As with the PMIGG, the principal control devices are an orifice located in the product stream and an inlet pressure regulator.

Boeing has performed fire protection research for the Air Force Aero Propulsion Laboratory under Air Force Contract F33615-84-C-2431. As a task under this contract, the Air Force requested that Boeing:

- o Assess all new OBIGGS technology and identify particular technologies that would provide a significant improvement in performance over the systems tested from 1983 to 1985 (i.e., the DOW PM ASM and the Clifton MS ASM).

- o Experimentally evaluate at least one advanced ASM in order to validate performance claims.

The technology assessment was addressed separately in an ASM technology survey and the results are summarized in Appendix B. This technical report however, deals solely with the experimental evaluation of the A/G Technology and Permea ASMs.

Acting on the results of the technology assessment, the capabilities of A/G Technology were more closely examined. Up to this point A/G Technology had been working under a Department of Energy contract making an ASM to produce oxygen enriched air (Reference 8). A/G Technology demonstrated the operation of an ASM roughly one inch in diameter. This demonstration was witnessed at the A/G Technology facilities and an audit of their instrumentation was conducted to certify observed performance. Based on the demonstration and audit, A/G Technology was deemed to have made valid measurements and to possess the potential for producing ASMs of exceptional performance for airplane installations.

Boeing sent out requests for proposals to all companies known to be working with ASM technology. Responses were received from A/G Technology and Applied Membrane Technology. Due to resource limitations and the fact that A/G Technology was well advanced in their product development, a single subcontract was awarded to A/G Technology to provide two 3 inch diameter ASMs, on a lease basis, for experimental evaluation.

Permea offered to supply an ASM on a loan basis, at no cost to Boeing or the Air Force, for testing in this program. A specific loan agreement was then concluded between Boeing and Permea so that the Permea ASM could be included in the testing. However, due to limitations in available test time the Permea unit did not undergo a complete array of tests as did the A/G Technology unit.

Prior to discussing details of the advanced membranes, it may be helpful to define certain terms:

Permeability: The rate of gas transport through a membrane wall per unit membrane thickness and unit partial pressure difference.

Separation Factor: The ratio of oxygen to nitrogen permeability. Higher separation factors will yield higher recoveries.

Recovery: The ratio of product or NEA flow to inlet flow, usually given in percent.

Efficiency: Same as recovery.

Product Flow: The flow rate of NEA.

Waste Flow: The flow rate of oxygen enriched gas which is considered a reject stream and is usually dumped overboard.

Productivity: The product flow rate obtainable with a specific size ASM operating at a fixed inlet pressure, altitude, temperature and NEA concentration.

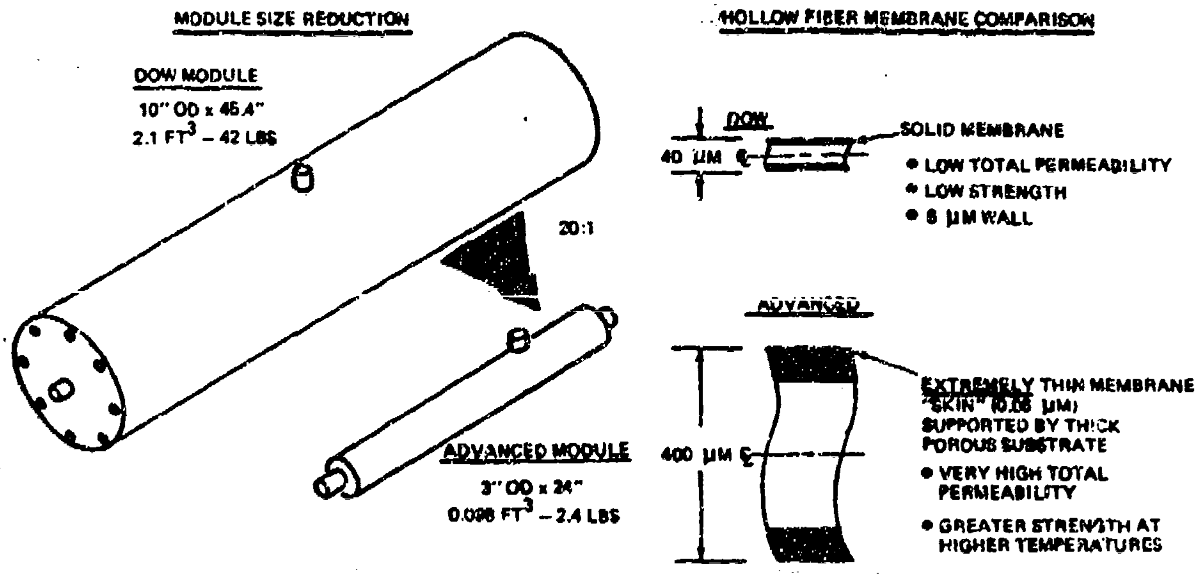


Figure 2. Advanced Membrane Improvements

The technology behind these advanced membranes is depicted in Figure 2 and is based on new fiber compositions. The DOW fiber was very small (roughly 40 micron OD, about the size of a human hair) with a solid membrane wall approximately five microns thick. Since oxygen permeation through the membrane wall is indirectly proportional to the membrane thickness, the thinnest possible membrane wall is desired. The new approach to making these fibers yields a fiber roughly an order of magnitude larger in diameter (varies among manufacturers) with a porous wall (substrate). However, the separation does not occur across the entire wall but at a very thin "skin" on the outside of the fiber, much less than one micron thick. The "skin" thickness varies among manufacturers and is highly proprietary. Hydraulic flow actually takes place through the porous substrate. This results in significantly greater permeability while also yielding larger diameter fibers of higher strength and flexibility. All current membrane development applicable to OBIGGS is based on this type of hollow fiber.

The polymer materials used in the membrane formulations determine the operating characteristics. In order to effectively separate gases, the membrane must be used at temperatures at or below the so-called glass transition temperature. The NEA flow rate generally increases as the temperature approaches the glass transition temperature. Above the glass transition temperature, the polymer softens and suffers a permanent drop in separation factor.

1.2 Performance Goals

For airplane applications, performance improvements over present systems would fall into one or more of the following categories:

- o Decreased Weight
- o Smaller Physical Size
- o Lower Operating Pressure
- o Higher Operating Temperature
- o Increased Efficiency
- o Higher Reliability

The higher operating temperature and increased efficiency both combine to reduce the weight and bleed air penalty for delivering and cooling the bleed air.

1.2.1 Weight

As with any airplane component, the weight of an OBIGGS effects airplane performance. For example, an OBIGGS proposed for a KC-135 would add about 700 pounds to each airplane (Reference 7). The ASM is estimated to make up 60 percent of this weight. Reduction of system weight would reduce airplane performance penalties. A recent study applying OBIGGS technology to an "ATF like" airplane (Reference 9) indicated gross takeoff weight would increase by 6 pounds for every pound of equipment in order to preserve constant range.

1.2.2 Physical Size

For fighter type airplanes, the system's volume can be even more critical than its weight. The permeable membrane ASM tends to be a low density system, requiring large volumes for installation on an airplane. A more compact OBIGGS would provide significant packaging advantages.

1.2.3 Operating Pressure

An OBIGGS requiring inlet pressures above the available engine bleed air pressure will require a "front end" compressor. This will in-turn impact the reliability of the system by adding further mechanical complexity. The requirement for a compressor must also be added to the ASM weight penalty. The energy required to operate the compressor must also be considered. Operation of an OBIGGS on available bleed air pressure is highly desirable.

1.2.4 Operating Temperature

An OBIGGS which requires inlet air temperatures below the aerodynamic recovery temperature can not cool the bleed air solely with a ram air heat exchanger and will need an air conditioning package (usually an air cycle machine) to lower inlet air temperatures. Systems which could operate at temperatures above those for the current PM and MS systems (40-75°F) would be a step in the right direction. Although recovery temperatures for supersonic airplanes can reach the 400°F range, any increase in allowable operating temperature would at least reduce (if not eliminate) the need for cooling systems other than ram air heat exchangers. For supersonic airplanes, the OBIGGS operating temperature could become more critical than weight or volume. The possibility of cooling ASM inlet air with fuel (which can reach temperatures in the neighborhood of 150°F in the fuel tanks) is an attractive approach for such airplanes.

Weight penalties for OBIGGS bleed air cooling systems are usually higher for retrofit airplanes than for new designs where the cooling load can be included in the baseline ECS capacity. In the retrofit case, the existing ECS normally cannot provide additional cooling for an OBIGGS. This leads to the need for an additional dedicated OBIGGS cooling system.

1.2.5 Efficiency

The engine bleed air penalties are significant, and therefore, OBIGGS with increased efficiencies are desirable. Bleed air required to operate an inlet air conditioning system must also be considered when calculating the efficiency for an OBIGGS. When analyzing bleed air cooling loads, one must consider both operating temperature and bleed flow. For example, the total bleed flow cooling load may actually decrease at lower ASM operating temperatures due to an overriding decrease in bleed flow that accompanies the increased efficiencies at lower temperatures.

1.2.6 Reliability

Reliability is paramount when considering the design of an OBIGGS. Substituting OBIGGS reliability problems for LN_2 logistics problems would be counter productive. Stored gas OBIGGS, where a high pressure compressor (2000-3000 PSI) is used to store NEA in bottles for use during short duration, high demand periods, is receiving much attention and has been chosen for the C-17 OBIGGS design. However, the reliability of the compressor is largely unknown.

If the performance of an advanced ASM, on a weight and volume basis, can be improved, an advanced direct flow OBIGGS could provide the required inert gas with a smaller and lighter package than the stored gas approach. Such a system would be inherently more reliable.

1.2.7 Normalized Performance

In order to compare the potential of different size systems from different manufacturers, their performance was normalized on a weight and volume basis during the initial technology survey. For example:

$$\frac{\text{Lbs/Min of 5\% } O_2 \text{ Product Gas}}{\text{Lb of ASM}} \quad \text{and} \quad \frac{\text{Lbs/Min of 5\% } O_2 \text{ Product Gas}}{\text{Ft}^3 \text{ of ASM}}$$

This normalization assumes that these values do not change significantly with scale. While this evaluation technique is admittedly a rough approximation, it allows simple yet meaningful comparisons between any type and size of ASM.

The A/G Technology and Permea ASMs tested in this program had non-optimized case hardware. Therefore weight projections were made assuming flight weight materials were used in the construction. Using this estimation procedure, weights can be compared for an arbitrary airplane application. This is valid procedure since the fibers and other internal components should be unaffected by the case material or thickness.

1.3 Objective and Approach

1.3.1 Objective

A test program was conducted to evaluate the performance of the A/G Technology and Permea advanced ASMs. The testing was designed to yield basic information about ASM performance as well as sensitivity to such environmental variables as vibration and moisture. The initial performance claims made by A/G Technology were based on rather small scale units (0.75 inch OD). This test program was designed to validate scaled-up performance with a 3 inch ASM (suitable for an ATF-like airplane stored gas system). The performance data were obtained over the widest range of operating conditions practical.

1.3.2 Approach

The approach was to conduct relatively inexpensive sub-scale tests on both the A/G Technology and Permea ASMs to provide data that can be applied to larger ASMs. Two separate and identical ASMs were obtained from A/G Technology in order to have a spare. Complete tests were not planned on both A/G Technology units unless problems were encountered with one unit. Permea provided two different ASMs but only data from the second unit were usable for this program. Due to Permea's late entry into the program, complete testing of their unit was not possible.

The tests were organized according to specific test objectives and a summary of the entire experimental program is shown in Table 1.

Table 1. Summary of Tests Conducted

Type of test	A/G	Permea
Performance envelope	X	X
2,000 hour endurance test	X	X
Moisture sensitivity and separation performance	X	
Hot/cold start-up	X	
On/off cycling	X	
Vibration sensitivity and mechanical response	X	
Hydrocarbon compatibility	X	X
Descent transient simulation	X	
Destructive high temperature test		X

The tests were essentially conducted in the order listed above. It was desired to obtain a good performance map of the unit before any significant number of operating hours were accumulated. The performance stability over time was checked after the performance envelope tests, while the potentially degrading tests were performed at the end of testing for obvious reasons.

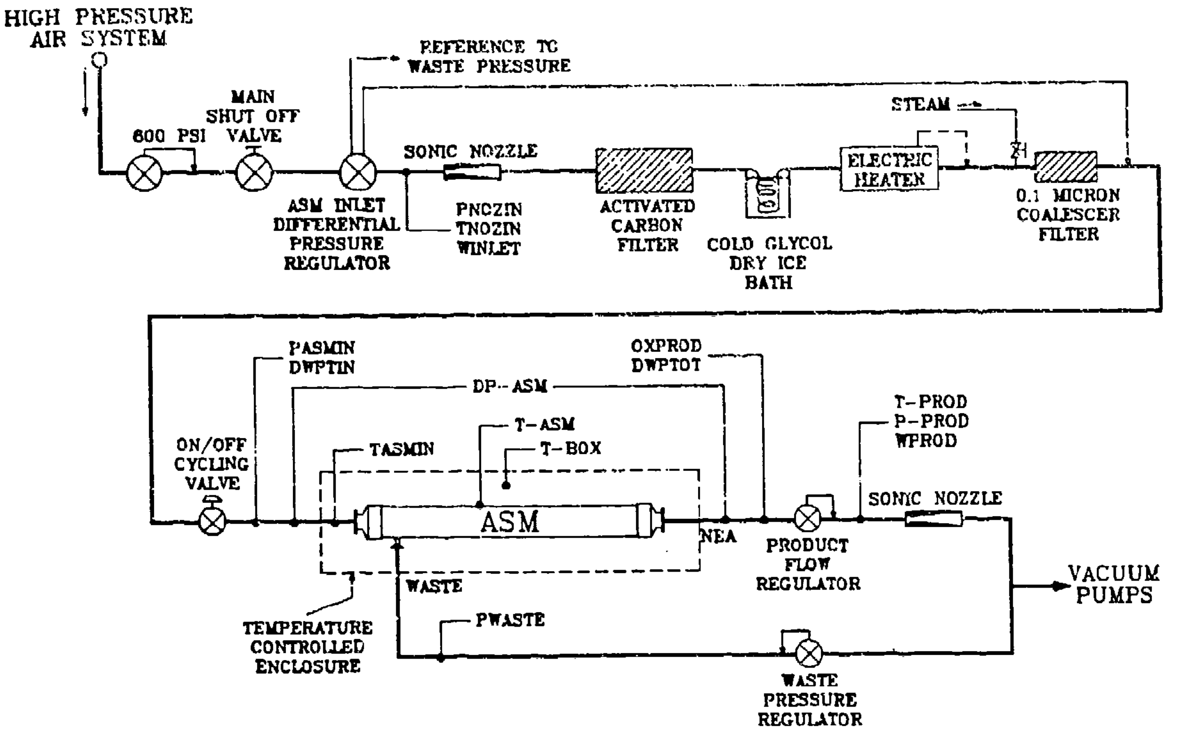
2.0 TEST SET-UP

2.1 Mechanical Description, Primary Test Set-Up

With the exception of the vibration tests and the Permea endurance test, a single test set-up was assembled which could handle all of the planned testing. The set-up (termed the primary test set-up) was initially designed and built to handle only the A/G unit and then adapted to both the A/G Technology and Permea ASMs. A schematic and photograph of this set-up are shown in Figure 3.

The following description refers to the Figure 3 schematic. High pressure air, from a 2000 PSIG compressor and storage tank, was used to conduct all tests except the vibration test. The air was first reduced in pressure to approximately 600 PSIG before entering the ASM inlet differential pressure regulator. This regulator controlled ASM inlet pressure while being referenced to ASM waste pressure. The outlet of the regulator was connected directly to the inlet sonic flow meter. Two different size nozzles were used (0.0685 inch ID for A/G Technology & 0.0362 inch ID for Permea) since the two ASMs were of significantly different flow capacities. With this pressure control scheme, the inlet pressure regulator would pass the flow required to maintain its pressure setting while using a sonic nozzle for flow measurement. Since the inlet pressure regulator was a differential regulator referenced to waste pressure, it automatically maintained a constant pressure difference across the ASM fibers independent of waste pressure. Inlet pressures are referred to in this report as gage pressure referenced to waste. This allowed changes in waste pressure (altitude) to be made, during mapping tests for example, without affecting inlet gage pressure. The sonic nozzle had an efficient 4° diffuser which allowed it to remain choked at pressure ratio's of 0.85 or higher.

Next the flow passed through the cooling glycol bath and the electric heater for temperature conditioning. The glycol bath was cooled with quantities of dry ice when ASM inlet air temperatures below room temperature were desired. The electric heater was controlled with an electronic closed loop controller to maintain a constant ASM inlet temperature regardless of flow. When the cold glycol bath was used, it produced temperatures below the desired set point which



NOTE: See Table 2 for mnemonic descriptions.

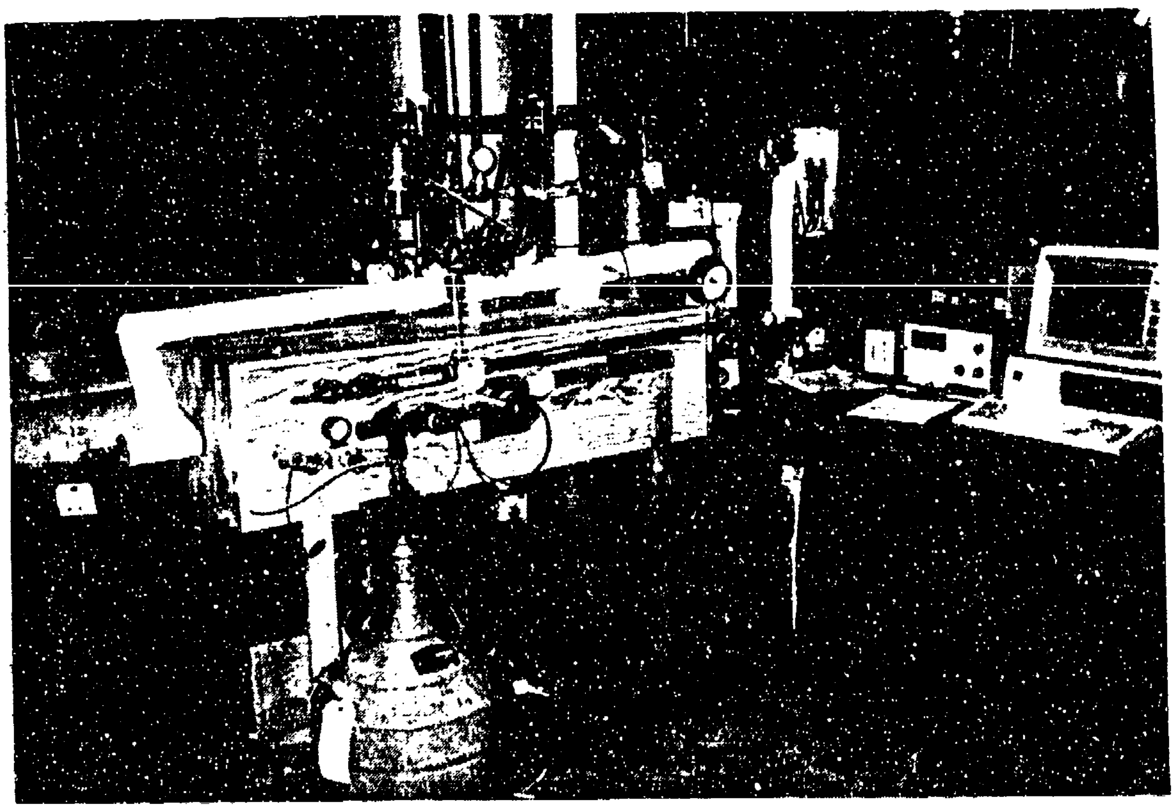


Figure 3. Advanced ASM Primary Test Set-Up

required that the inlet heater be operated in order to accurately trim the ASM inlet temperature to the desired setting. This proved to be an effective temperature control scheme.

The primary test set-up was modified during the endurance testing by installing carbon filters in place of the glycol bath. First a single carbon filter and latter a second was installed to adsorb oil vapor contaminants. These filter elements were Balston Type C1 and each contained 360 grams of activated carbon, theoretically capable of adsorbing 25 percent to its weight in hydrocarbons.

After the air was heated to the desired temperature in the electric heater, it then passed through a 0.1 Micron Balston Grade BX coalescing filter (rated 99.99 percent efficient) prior to entering the ASM. For moisture tests, steam was added upstream of the coalescer filter and any small amounts of condensate were continuously drained from the bottom of the coalescer.

An air operated shutoff valve was installed immediately upstream of the ASM for use during the on/off cycling and start-up tests. Once activated, this valve would open in approximately 0.2 seconds. It was located immediately upstream of the ASM inlet to produce a rapid rise in inlet pressure.

The waste flow exited the ASM through two fittings on the side of the case and directly entered the waste pressure regulator. This regulator was a differential pressure regulator referenced to a vacuum provided by a small independent vacuum pump. The regulator then functioned as an absolute pressure regulator independent of waste flow or any other ASM operating parameter. The downstream side of the waste pressure regulator was connected to two large Kinney KD-780 vacuum pumps having a total capacity of 1300 ACFM. This system easily allowed ASM testing at waste pressures as low as 2.0 PSIA (46,000 Ft altitude) and up to 14.7 PSIA.

The product oxygen concentration was sampled immediately downstream of the ASM prior to entering the product flow regulator. A small portion of the NEA flow was diverted to a fast response Sensormedics (previously a Division of Beckman) Model OM-11EA oxygen analyzer. A selector valve was also used to provide nitrogen and oxygen calibration sources for the analyzer. The oxygen sampling system (including analyzer) produced a stable measurement in approximately 10 seconds or less depending on the magnitude of the change in $\%O_2$.

The product flow regulator was essentially an absolute pressure regulator (referenced to an independent vacuum like the waste pressure regulator) feeding a sonic nozzle. As with the inlet nozzles, two different size nozzles were used (0.1367 inch ID for A/G Technology & 0.0564 inch ID for Permea). The sonic nozzle incorporated an efficient 4° diffuser and was connected to the large Kinney vacuum pumps to allow choked flow at inlet pressures well below ambient. This scheme allowed accurate measurements over a wide range of flows. The product flow was therefore independent of changes in other ASM operating parameters (unless ASM outlet pressure dropped below the regulator setting).

The ASM was enclosed in an insulated box which was independently temperature controlled to any desired temperature from -60°F to +140°F. An electric heater, located inside the box, was used for temperatures above ambient while the addition of controlled amounts of LN_2 was used for temperatures below ambient. A small fan was continuously operated inside the box to eliminate undesirable thermal gradients.

2.2 Instrumentation Description, Primary Test Set-Up

The instrumentation measurements have been noted in Figure 3 and are listed separately in Table 2. Equations used to calculate mass flowrates are included in Appendix C. The mass flow measurements accounted for such things as changing nozzle discharge coefficient with throat Reynolds number, flow to the oxygen analyzer, changes in gas constant with oxygen concentration and real gas effects in order to achieve the maximum flow measurement accuracy practical. The product oxygen analyzer was regularly checked on both N_2 (0 percent O_2) and a 9 percent O_2 calibration gas (span) in order to assure accurate product oxygen concentration measurements. All measurements were continuously displayed on a CRT for the operator and logged on an IBM-PC based data acquisition system also shown in Figure 3.

Table 2. Instrumentation Measurements, Primary Test Set-Up

Mnemonic	Description	Range	Instrument accuracy	Measurement resolution
	Temperatures:			
TNOZIN	Inlet nozzle temp	Ambient	(Note 1)	0.1°F
TASMIN	ASM inlet temp	-60 to 300°F	(Note 1)	0.1°F
T-ASM	ASM temp	-60 to 300°F	(Note 1)	0.1°F
T-BOX	Box temp	-60 to 300°F	(Note 1)	0.1°F
T-PROD	Product nozzle temp	-60 to 300°F	(Note 1)	0.1°F
	Pressures:			
PNOZIN	Inlet nozzle pres	650 psia	0.1% fs	0.3 psi
PASMIN	ASM inlet pres	135 psia	0.01% fs	0.07 psi
DP-ASM	ASM differential pres	10 psid	0.15% fs	0.005 psi
PWASTE	ASM waste pres	16 psia	0.1% fs	0.01 psi
P-PROD	Product nozzle pres	135 psia	0.05% fs	0.07 psi
	Other data:			
OXPROD	Product % O_2	0 to 20.9%	0.1% O_2	0.01% O_2
DWPTIN	Inlet dew pt (note 2)	-40 to +140°F	0.4°F	0.1°F
DWPTOT	Product dew pt (note 2)	-40 to +40°F	0.4°F	0.1°F
	Mass flows:			
WINLET	Inlet mass flow rate	3 ppm	2%	0.001 ppm
WPROD	NEA mass flow rate	2 ppm	2%	0.001 ppm

Notes:
1. ±5°F per thermocouple wire specifications, ±0.1°F measurement jitter, ice point checked to within ±0.5°F.
2. The single dew point instrument was mechanically switched to sample either inlet or product gas.

With all data continuously displayed on a CRT in the desired engineering units, the operator could control ASM operating parameters by making adjustments to pressure regulators and temperature controllers until the desired conditions were achieved. The operator would then command the computer to log the current data to disk. This procedure was used for all non-time varying data. During transient type tests, like on/off cycling or hot/cold start-up, the computer automatically logged data to disk at a set rate. This permitted time varying data to be reliably acquired and latter plotted.

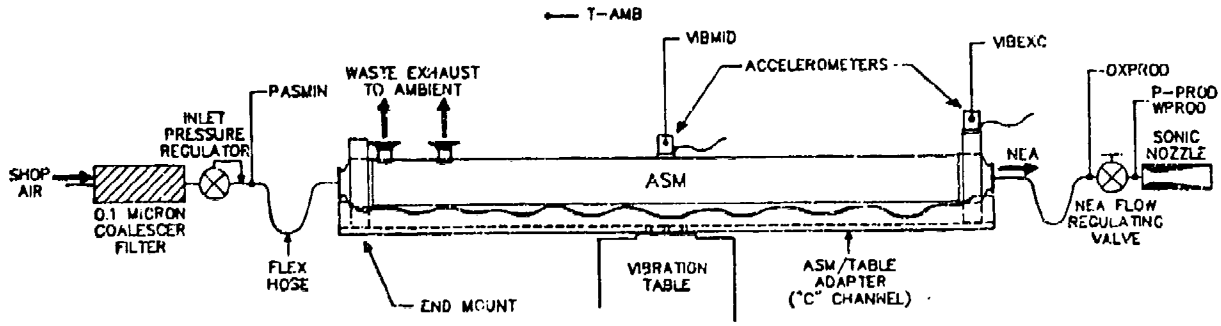
The moisture content of the inlet air and NEA was measured with a single General Eastern Model 1200 APS Dewpoint Hygrometer. This hygrometer operated on a chilled mirror principal and measured dew points at the pressure of the sample, referred to as a "pressure dew point". It was necessary to provide the single hygrometer a small continuous sample of gas (0.002 PPM) from the inlet air and NEA via a switching valve. The entire system (sample lines, valves, hygrometer, etc) was heated for dew points above ambient temperature. Although the hygrometer is factory calibrated and does not require periodic calibrations, separate sources of dry N_2 and 32°F dew point air (ice bath conditioned) were used for periodic calibration checks.

In order to maximize instrumentation accuracy, end-to-end calibrations were performed in-place using pressure and temperature standards, such as dead weight testers and ice baths, along with certified primary standard oxygen mixtures for the oxygen analyzer. Although the flow meters (inlet and NEA sonic nozzles) were not calibrated, they were fabricated according to ASME guidelines and periodically checked in place against each other. The method of checking the two sonic nozzles against each other consisted of closing a valve in the waste flow line and comparing the inlet versus product flows. Under this condition the two meters always read within 2 percent of each other. In addition to this flow meter check, the entire test set-up was regularly leak checked by pressurizing the ASM and entire plumbing arrangement, closing all inlet and outlet valves and measuring the leak down rate.

2.3 Vibration Test Set-Up

A schematic and photograph of the vibration test set-up are shown in Figure 4. The ASM was mounted at both end fittings by a clamping arrangement which was attached to a common mounting beam. The mounting beam was in turn mounted to a Ling Model SC0300 vibration table. The decision to mount the ASM at the two end fittings was based on the fact that most of the weight is in the end fittings and tube sheet (See Table 6). The test set-up allowed the ASM to be operated over the entire range of vibration frequencies of interest as well as determine the response of the ASM relative to the input vibration level at the end mounts. An accelerometer was mounted at one end mount and at the center of the ASM on the plastic shell. The instrumentation measurement locations are shown in Figure 4 and described in Table 3.

The inlet air source was a low pressure "shop" air supply which was first filtered and then regulated to the desired ASM inlet pressure. The simplicity dictated by this set-up precluded any inlet flow measurement. The waste flow was vented directly to ambient since from a vibration interference standpoint it was desirable to make no connections to the waste ports. The product flow was connected to the oxygen analyzer prior to passing through the product flow meter (sonic nozzle). No attempt was made to condition the inlet air to other than ambient temperature.



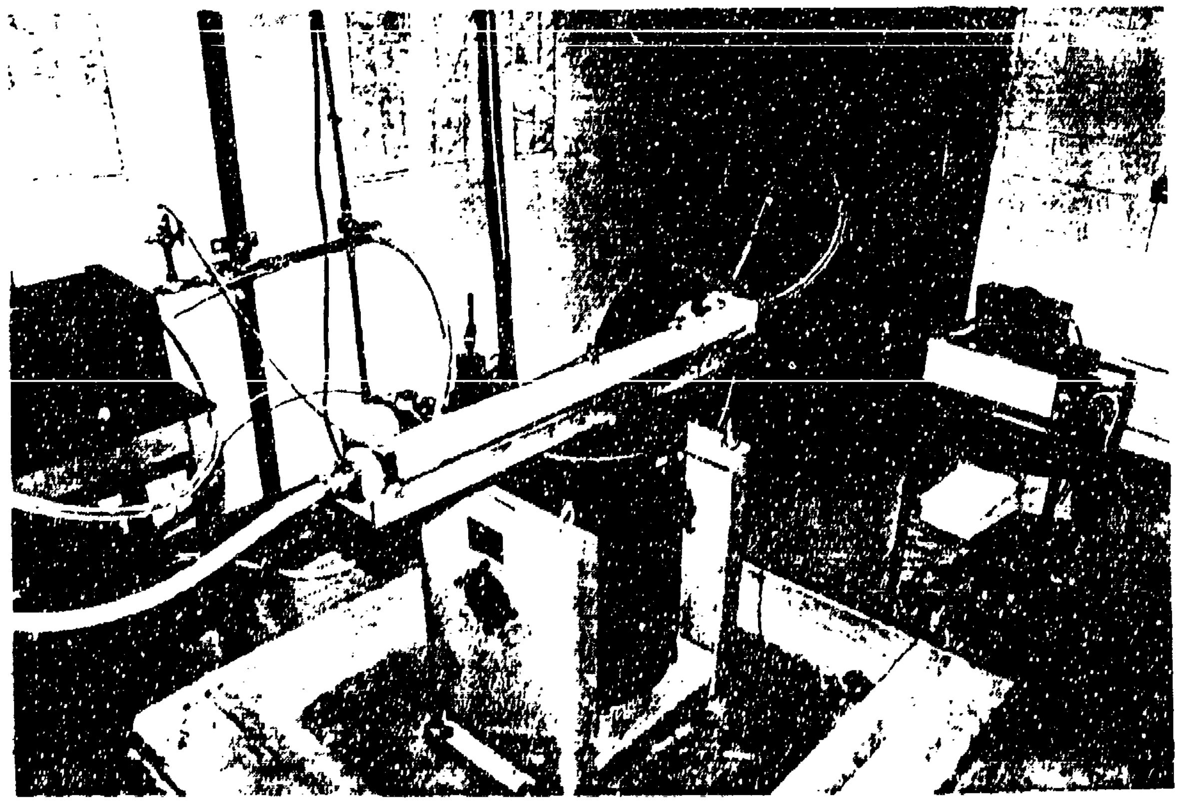


Figure 4. Vibration Test Set-Up

Table 3. Instrumentation Measurements, Vibration Test Set-Up

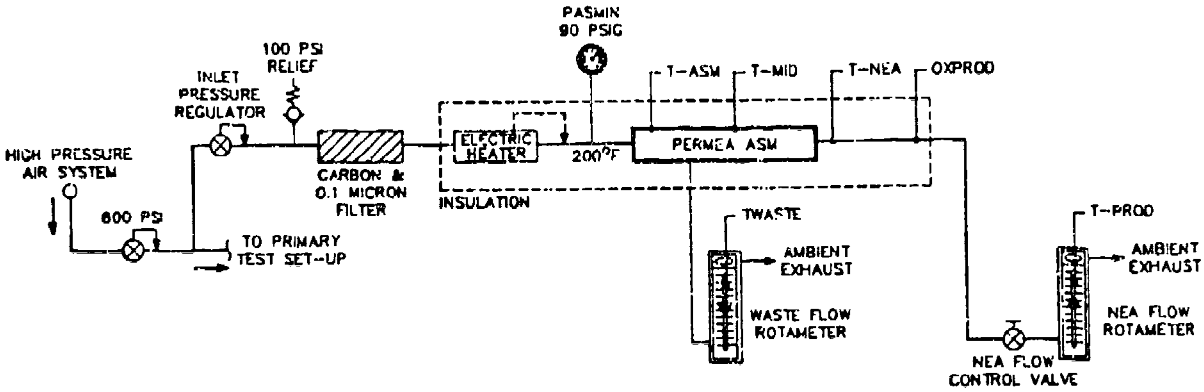
Mnemonic	Description	Range	Instrument accuracy	Measurement resolution
	Temperatures:			
T-AMB	Room temp	Ambient	5°F	0.1°F
	Pressures:			
PASMIN	ASM inlet pres	100 psig	0.07% fs	0.02 psi
P-PROD	Product nozzle pres	100 psia	0.06% fs	0.02 psi
	Other data:			
OXPROD	Product % O_2	0 to 20.9%	0.1% O_2	0.01% O_2
VIBEXC	Vibration input	10 G's	0.1 G	0.1 G
VIBMID	Vibration @ ASM center	100 G's	0.1 G	0.1 G
	Mass flows			
WPROD	NEA mass flow rate	2 ppm	2%	0.001 ppm

2.4 Permea Endurance Test Set-Up

In order to permit long term endurance testing of both the A/G Technology and Permea ASMs simultaneously, a second auxiliary test set-up was fabricated. Testing both units in parallel meant that the 2000 hour endurance test could be performed in three months rather than six. While the A/G Technology unit was accumulating hours in the primary test set-up described in Section 2.1, the Permea unit was operating in the auxiliary set-up.

While the auxiliary set-up did not incorporate the same high accuracy instrumentation as the primary, it was an adequate and inexpensive method of significantly reducing test time. A schematic and photograph of the auxiliary set-up is shown in Figure 5. Referring to Figure 5, the inlet air was derived from the same 600 PSIG pressure reducing regulator as the primary set- up. This was further reduced to the desired ASM inlet pressure (90 PSIG) by a simple regulator referenced to ambient pressure. Before entering the ASM, the air passed through a Balston grade BX filter (0.1 Micron) and the inlet air heater. Two filter elements were available, a plain particulate/coalescer element and an activated carbon element.

The inlet air temperature was controlled by an electronic temperature controller to deliver 200°F air at the ASM inlet. The ASM was not enclosed in a temperature controlled enclosure but was instead heavily insulated. This resulted in a temperature gradient along the ASM although the gradient remained



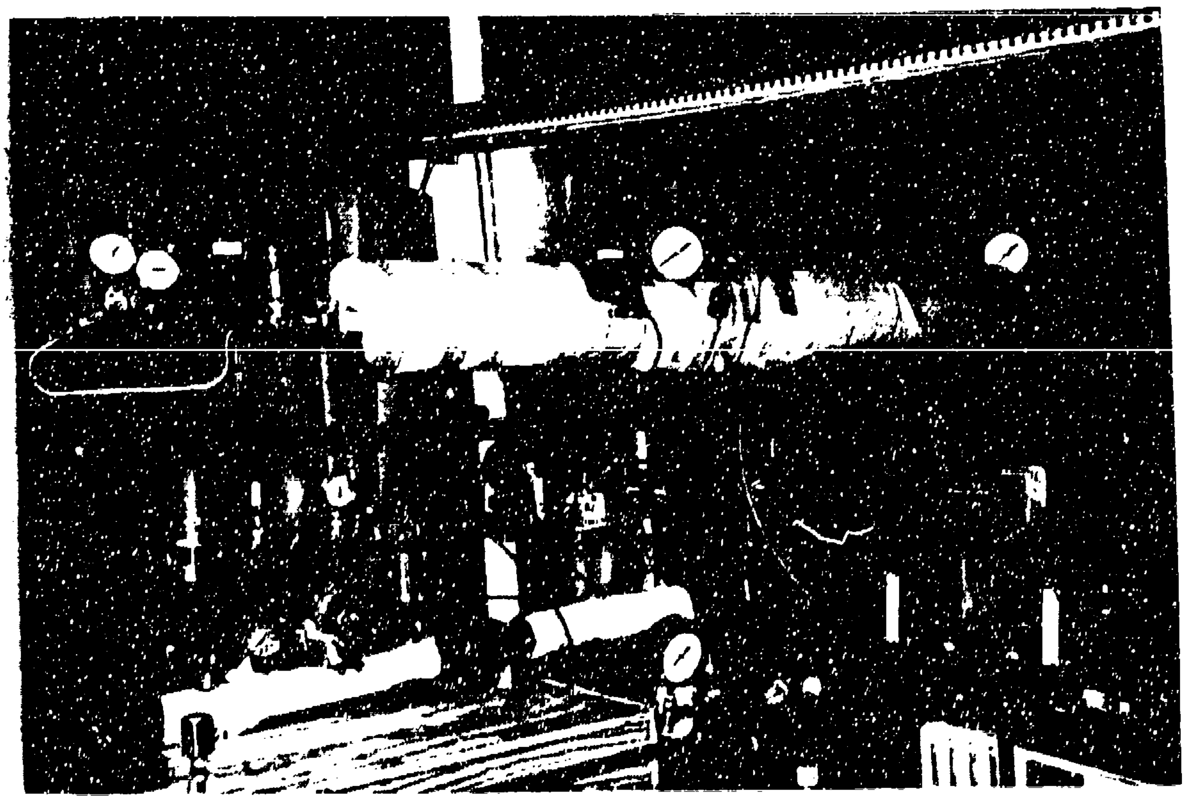


Figure 5. Permea Endurance Test Set-Up

nearly constant during the duration of the three month test. Typical temperatures were 200°F, 187°F and 177°F at the inlet, mid point and product end of the ASM respectively.

The inlet air flow was not measured, but rather the waste and product flows were metered using rotameters. This provided reasonable accuracies for the purposes of the endurance test. The NEA oxygen concentration was measured with the same analyzer as the primary set-up.

The instrumentation measurement locations are shown in Figure 5 and described in Table 4. Data from this auxiliary set-up was logged manually on a daily basis over a three month period. Inlet pressure was measured with an ordinary Bourdon Tube type pressure gage calibrated at 90 PSIG.

Table 4. Instrumentation Measurements, Permea Endurance Test Set-Up

Mnemonic	Description	Range	Instrument accuracy	Measurement resolution
	Temperatures:			
T-ASM	ASM case temp @ inlet	Amb to 200°F	(Note 1)	0.1°F
T-MID	ASM case temp @ mid point	Amb to 200°F	(Note 1)	0.1°F
T-NEA	NEA temp @ ASM outlet	Amb to 200°F	(Note 1)	0.1°F
TWASTE	Waste rotameter gas temp	Amb to 200°F	(Note 1)	0.1°F
T-PROD	NEA rotameter gas temp	Amb to 200°F	(Note 1)	0.1°F
	Pressures:			
PASMIN	ASM inlet pres	90 psig	0.2 psi	0.2 psi
P-AMB	Ambient pres	Ambient	0.05 psi	0.01 psi
	Other data:			
OXPROD	Product % O_2	0 to 20.9%	0.1% O_2	0.01% O_2
	Mass flows:			
WWASTE	Waste mass flow rate	0.25 ppm	2%	0.001 ppm
WPROD	NEA mass flow rate	0.25 ppm	2%	0.001 ppm

Notes:
1. ± 5°F per thermocouple wire specifications, ± 0.1°F measurement jitter, ice point checked to within ± 0.5°F.

3.0 ADVANCED ASM DESCRIPTIONS

3.1 A/G Technology ASM Description

Two, essentially identical, advanced ASMs were obtained from A/G Technology. A photograph and dimensioned drawing of the A/G Technology advanced ASM are shown in Figure 6. General specifications for the two ASMs are given in Table 5. However, as mentioned above, the fiber and ASM internal construction details are proprietary. Although both ASMs were essentially identical, ASM #2 contained certain unspecified improvements.

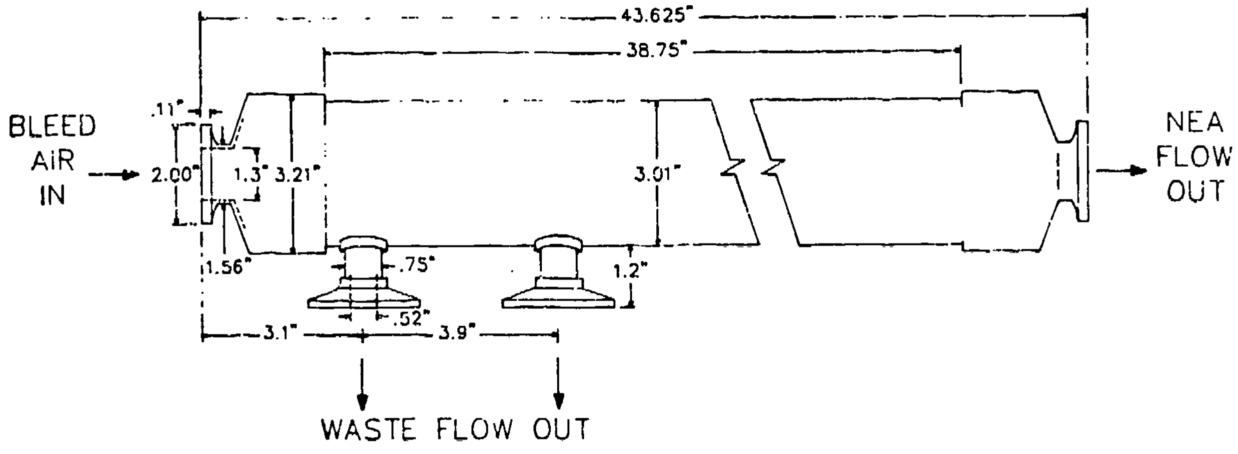
Table 5. A/G Technology Advanced ASM Specifications

Item	Module #1 (S/N:6A-G/1300501AL)	Module #2 (S/N:28H500201AL)
ASM overall length (in)	43.6	43.6
ASM overall diameter (in)	3.2	3.2
ASM overall weight (lbs)	4.0	4.16
Tube sheet/fiber bundle dia (in)	2.56	2.56
Approx. active fiber length (in)	39	39
Bulk volume of active fiber (in^3)	201	201
End fitting/case mat'l	Polysulfone	Polysulfone
Fitting style (inlet, NEA, waste)	1.5" tri-clamp	1.5" tri-clamp
Mfgr model no.	GS-SEI-75X	GS-SEI-75X
Rated NEA flow (ppm)*	0.85/0.38	0.79/0.36
Rated NEA recovery (%)*	46/29	45/29

*9/5 %O_2, 60 psig, 30,000 ft altitude, 100°F.

Table 6. A/G Technology Advanced ASM Weight Breakdown

Component	Weight (lbs)	Percentage of total
Membrane fibers	1.32	33
Tube sheet potting compound	0.36	9
Fittings (inlet, NEA, waste)	0.32	8
Shell (3" polysulfone tube)	2.00	50
Total	4.00 lbs	100%



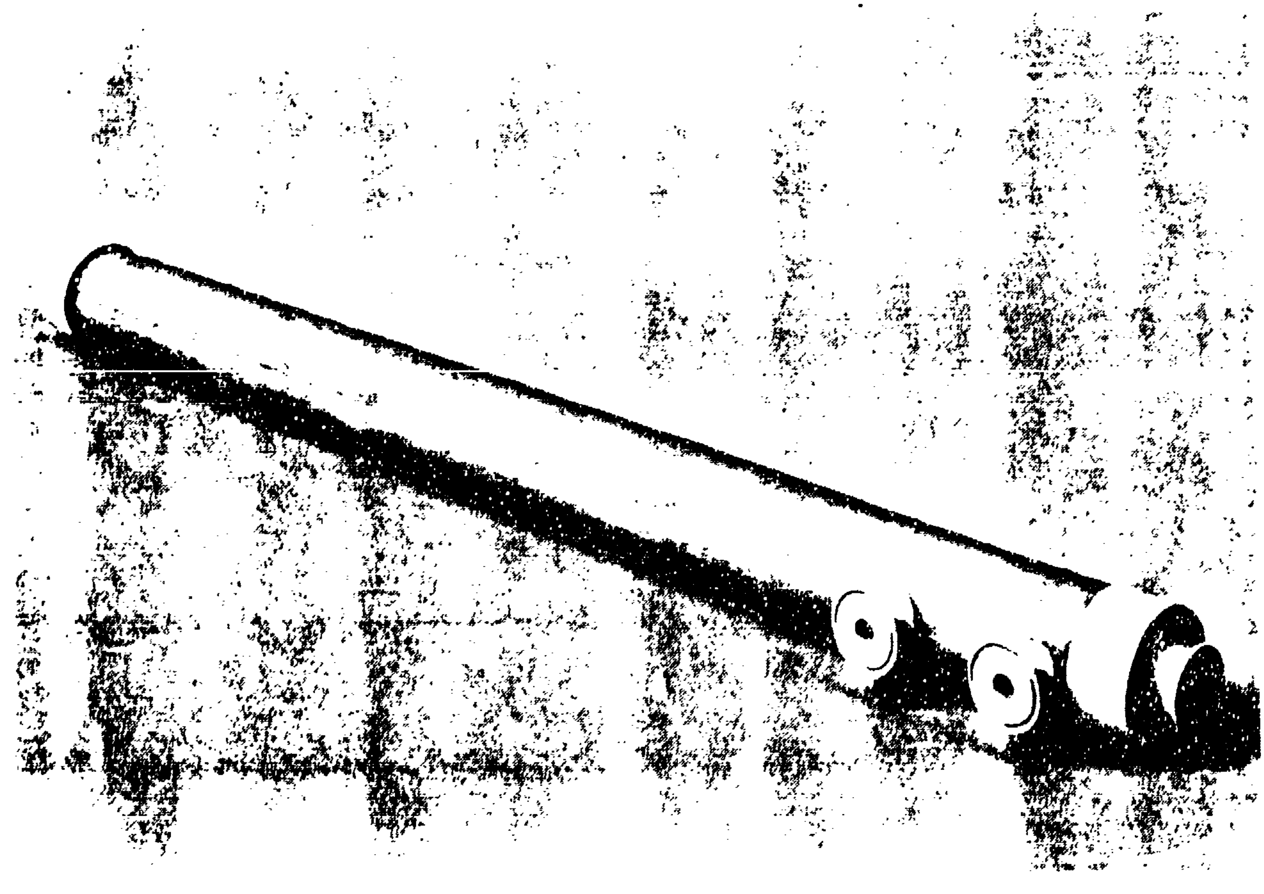


Figure 6. A/G Technology Advanced ASM

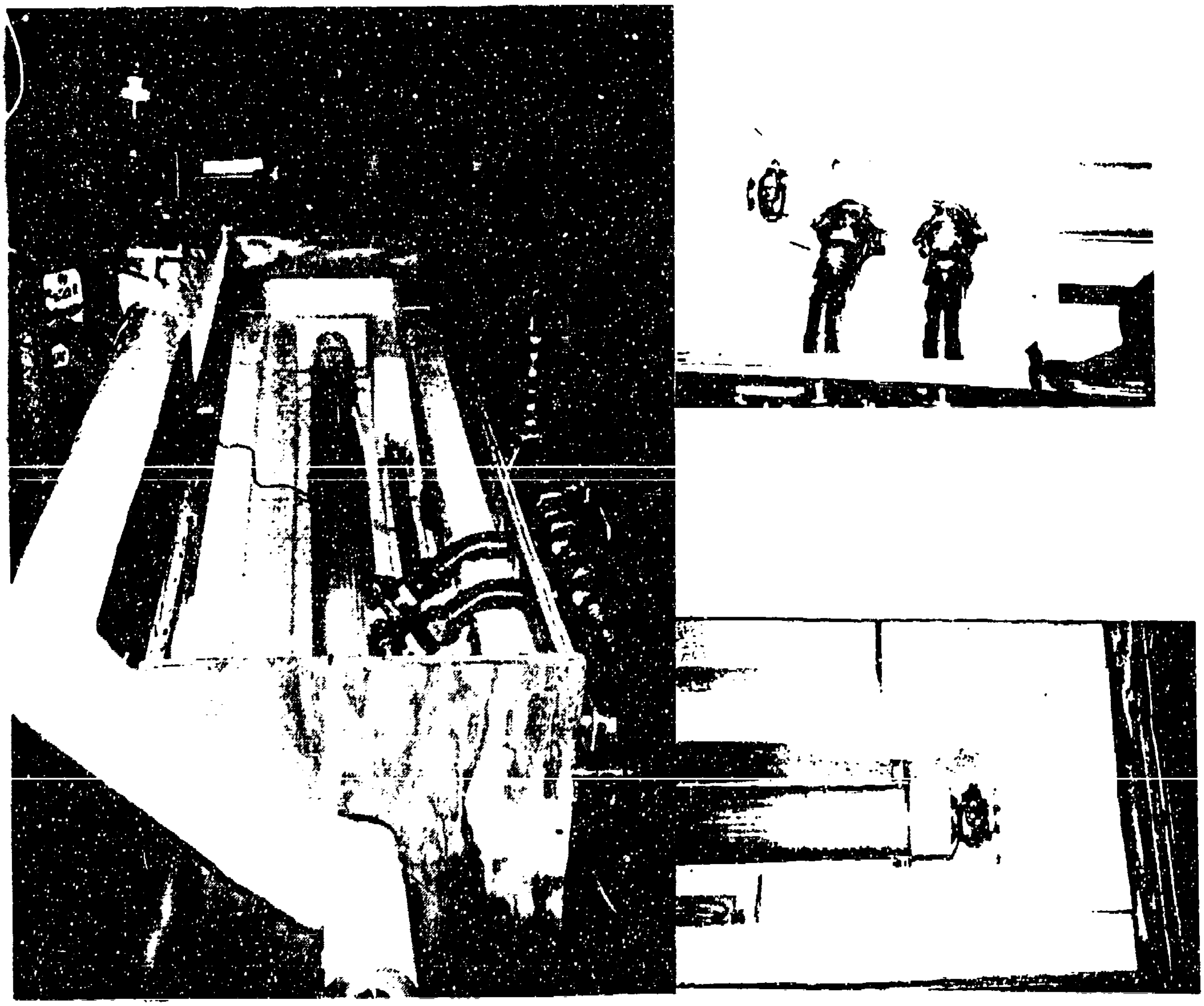


Figure 7. A/G Technology ASM Installation

A weight breakdown of the individual components which make up the ASM is given in Table 6. The shell of the ASM was a 3 inch OD clear polysulfone tube with a wall thickness of approximately 0.1 inch. This shell was designed to withstand a 150 PSIG burst pressure for these ground tests only. This requirement would not exist for airplane applications. The shell design requirement for an airplane installation will probably be based on shell stiffness or fiber containment and not burst pressure.

Referring to Figure 6, the waste fittings are located on the side of the shell near the inlet. The NEA outlet is located at the opposite end of the ASM from the inlet. Installation of the A/G Technology ASM in the environmental enclosure, with inlet, waste and NEA connections, is depicted in Figure 7.

A/G Technology's maximum recommended operating pressure (applicable only to the two ASMs used in these tests) was a function of temperature and is shown in Figure 8. A/G Technology's final report, containing additional information, is included as Appendix A.

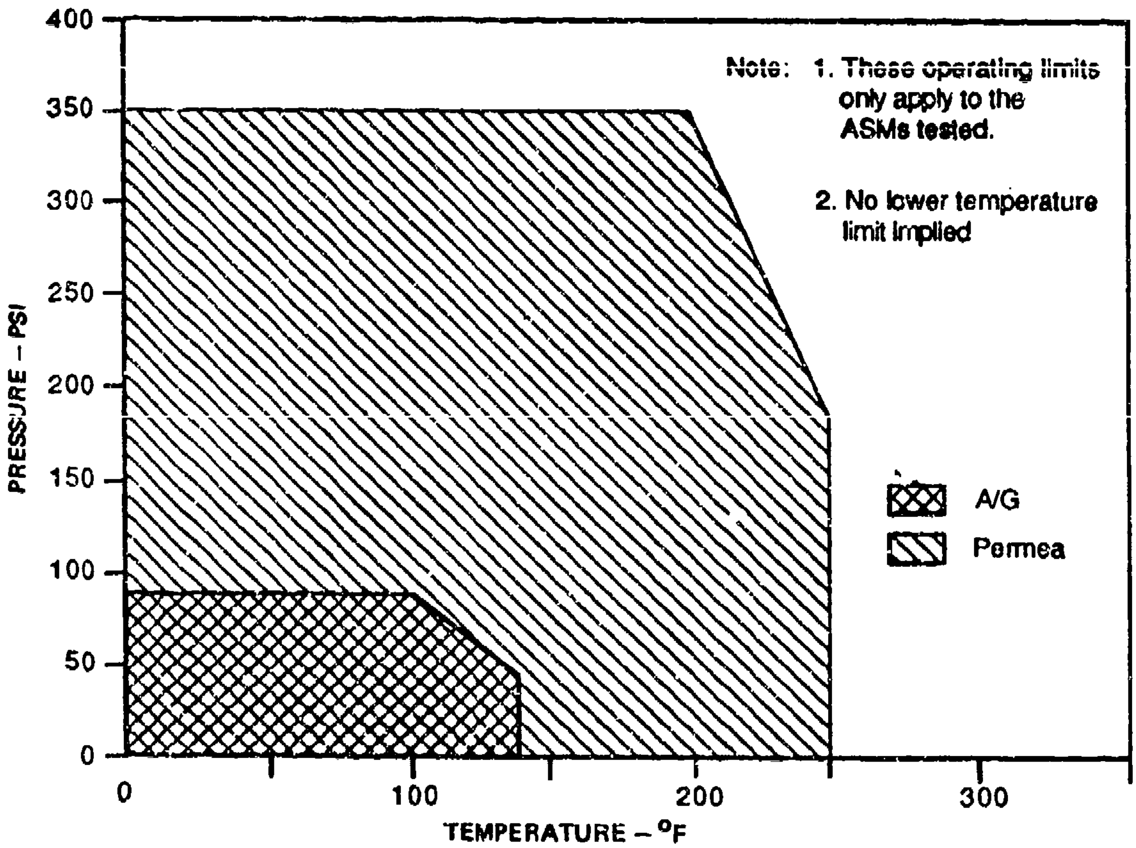


Figure 8. Suggested ASM Operating Limits

The fibers used in the A/G Technology ASM are manufactured in a proprietary process which produces what is termed an asymmetrical hollow fiber. In the cylindrical sense the fibers are symmetrical, but the asymmetrical term is used to describe the fiber wall which is mostly porous substrate with a very thin separating membrane skin. This construction yields a high strength fiber while at the same time incorporates a thin integral permeable membrane for high permeability. The thin membrane skin is the fundamental reason for the performance improvements over earlier membranes.

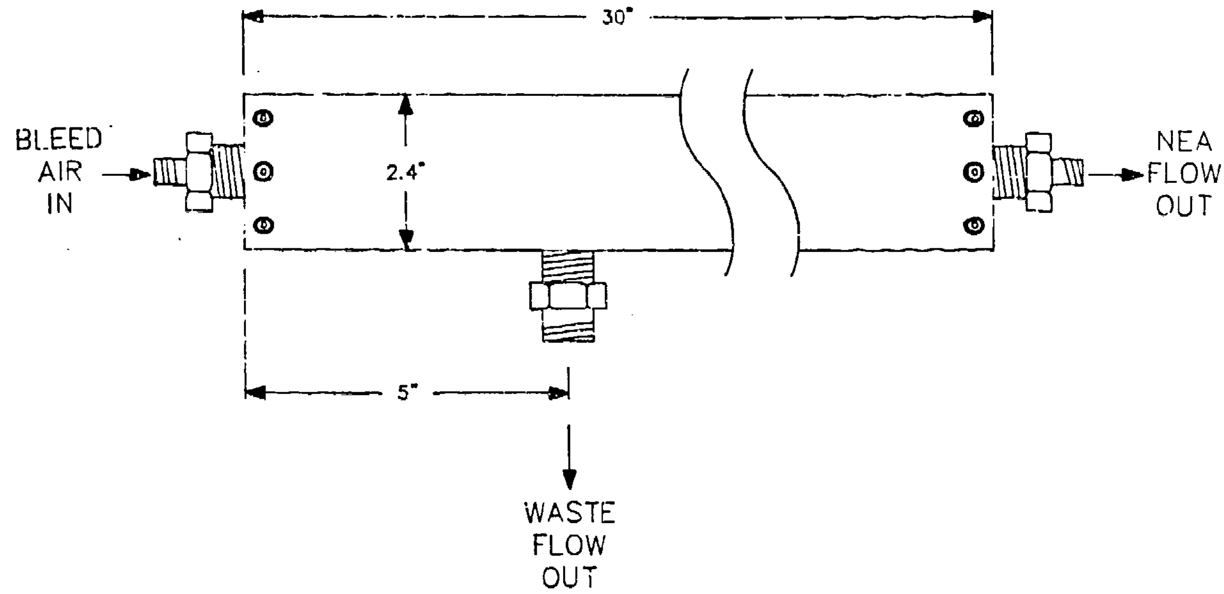
3.2 Permea ASM Description

Permea had provided two ASMs on a loan basis for testing during this program. The first unit was accidentally damaged by over-heating localized areas of the ASM case when heat tape was used to maintain elevated temperatures during testing (this ASM was too large to fit in the constant temperature enclosure). Only limited data were obtained with the first ASM before the damage occurred. Its performance will not be addressed in this report.

The second ASM provided by Permea incorporated fibers of a recently improved design. The second ASM was successfully tested and is described in this report. A photograph and dimensioned drawing of the Permea ASM are shown in Figure 9. General specifications for the Permea ASM are given in Table 7. As with the A/G Technology ASM, certain fiber and ASM internal construction details are proprietary. However, a limited amount of additional information is contained in Permea's final report (Appendix I).

The shell of the ASM was standard commercial 2 inch (2.4 inch OD) fiberglass pipe. This shell was designed to withstand at least a 150 PSIG burst pressure for these ground tests only. This requirement would not exist for airplane applications. The shell design requirement for an airplane installation will probably be based on shell stiffness or fiber containment and not burst pressure.

Referring to Figure 9, the waste fitting was located on the side of the shell near the inlet. The NEA outlet was located at the opposite end of the ASM from the inlet. The ends of the fiberglass pipe (inlet and NEA connections) were



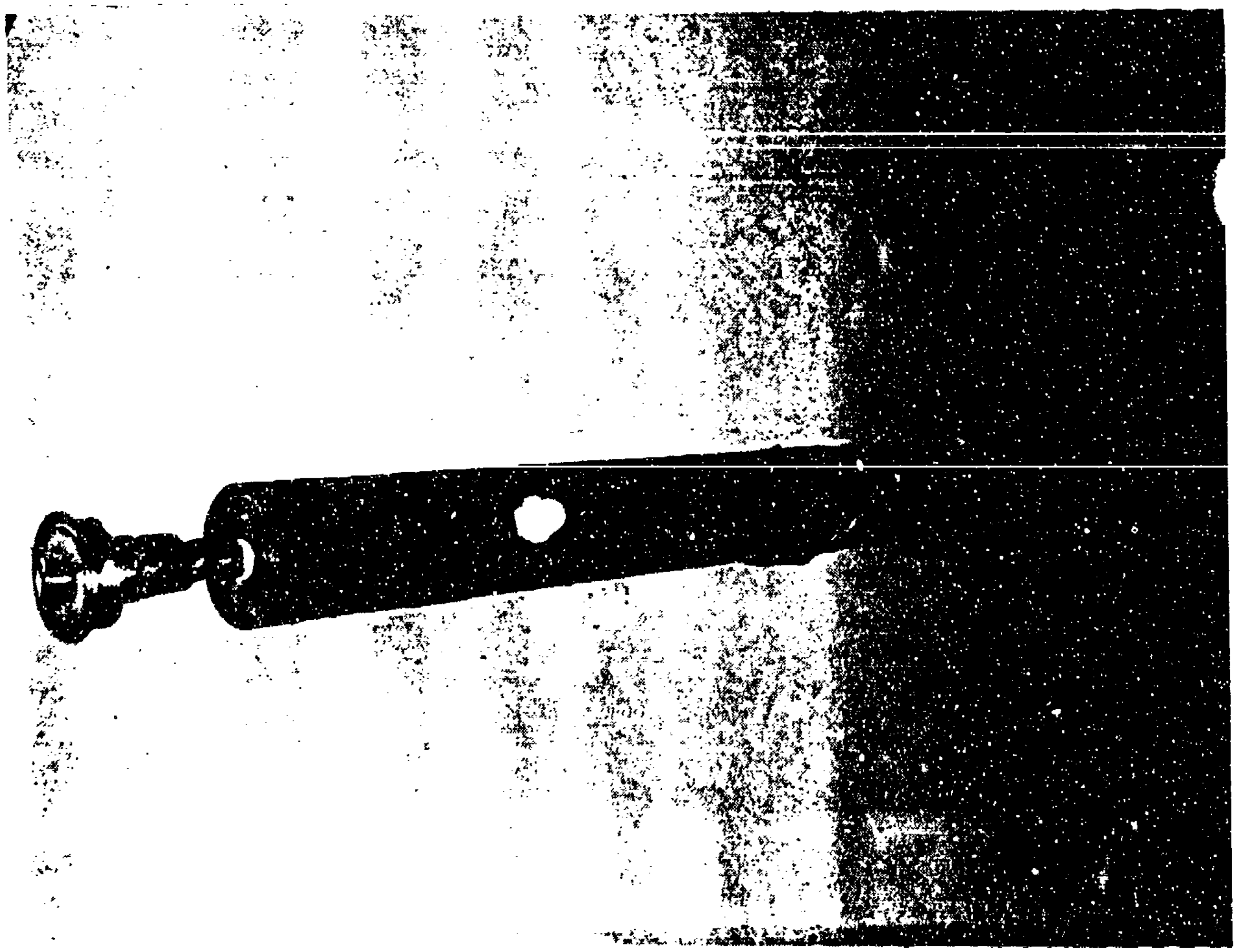


Figure 9. Permea Advanced ASM

Table 7. Perma Advanced ASM Specifications

ASM overall length (in)	30
ASM overall diameter (in)	2.4
ASM overall weight (lbs)	3.63
Tube sheet/fiber bundle dia (in)	2.1
Overall fiber length (in)	25
Active fiber length (in)	20.5
Bulk volume of active fiber (in^3)	71
Fiber weight (ibs)	0.4
Tube sheet weight (lbs)	0 7
Case mat'l	Fiberglass
Fitting style (inlet, NEA)	1/4" swagelock
Mfgr S/N	202-080
Rated NEA flow (ppm)*	0.100/0.052
Rated NEA recovery (%)*	56/39
*9/5 %0_2, 60 psig, 30,000 ft altitude, 200°F.	

fitted with steel inserts into which were threaded 1/4 inch Swagelock fittings. Installation of the Permea ASM in the environmental enclosure, with inlet, waste and NEA connections, is depicted in Figure 10.

Permea had suggested an initial operating temperature of 200°F. The allowable operating pressures were actually greater than the test set-up would permit (90 PSIG) and therefore were not approached during testing. The maximum operating pressure/temperature envelope is shown in Figure 8. The 250°F limit was intentionally exceeded at the end of the test program (see Section 4.8).

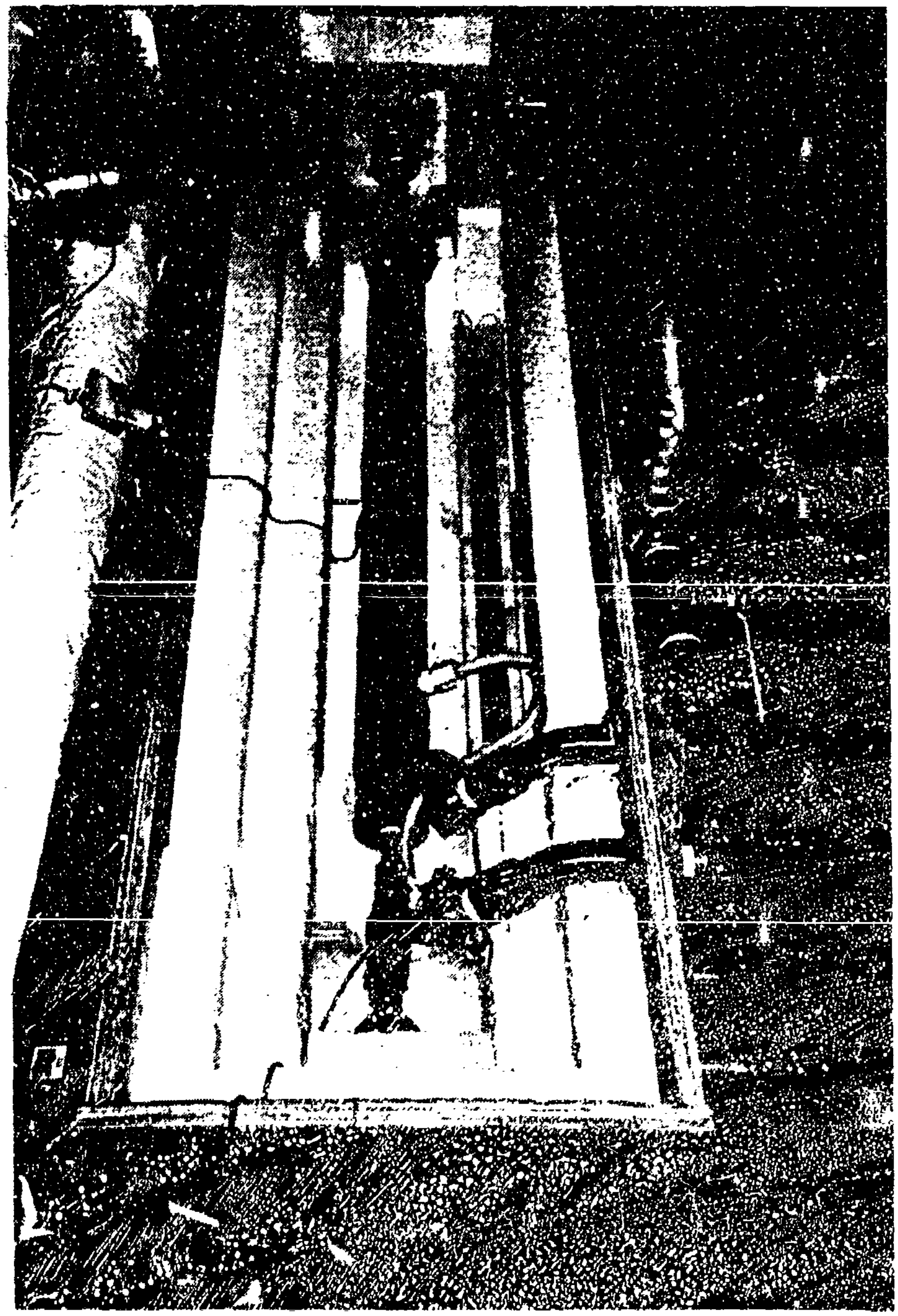


Figure 10. Permea ASM Installation

4.0 DESCRIPTION OF TESTS AND TEST RESULTS

4.1 Performance Envelope

Performances of the A/G Technology and Permea ASMs were measured at many different combinations of pressure, temperature, product flow rate, and altitude using the primary test set-up. The dependent variables were product $\%O_2$ and recovery (product flow/inlet flow). Except for the specific range of certain variables, both the A/G Technology and Permea ASMs were handled similarly during the performance envelope tests. The ranges for each of the independent variables are shown in Table 8.

Table 8. Performance Envelope Variable Ranges

	Variable Range	
Variable	A/G	Permea
NEA flow (ppm)	0 1 - 1 4	0 025 - 0 15
Inlet pressure (psig)	20 - 90	20 - 90
Temperature (°F)	50° - 140°	120° - 200°
Waste pressure (psia)	2 0 - 14.7	2 0 - 14.7
Note: 2.0 psia is equivalent to 46,000 ft altitude.		

Tests for all combinations of the four independent variables were not required. For example, the points which delivered greater than 12 $\%O_2$ were generally eliminated along with some combinations of high altitude and temperature.

When conducting the performance mapping, test conditions most easily changed were varied most frequently (product flow first, inlet pressure second, waste pressure third and temperature last). During these tests, the operator would establish the desired conditions by adjusting regulators and temperature controllers. When performance had stabilized, data were logged on the computer disk for storage and latter analysis.

4.1.1 A/G Technology Performance Envelope Test Results

Two ASMs were obtained from A/G Technology. Performance mapping was primarily accomplished using ASM #1 while leaving ASM #2 as a spare in the event that problems arose with #1.

The test matrix used for the A/G Technology ASM is shown in Table 9 and indicates the combinations of temperature, waste pressure, inlet pressure and product flow tested. The detailed and complete results of the performance envelope tests, in both graphical and tabular form, are included in Appendix D. However, selected results are also presented here in graphical form.

Table 9. A/G Technology Performance Envelope Test Matrix

Temp/waste pres combinations

Waste pres (psia)	Temperature (°F)				
	50	75	100	120	140
14.7	*	*	*	*	*
10.0			*		
5.0	*		*	*	*
2.0			*		

* Indicates tests at pres/flow combinations shown at right.

Blank indicates no test.

Pres/NEA flow combinations

NEA flow (ppm)	Inlet pressure (psig)					
	20	30	40	55	70[2]	90[1]
0.1	*	*	*	*	*	*
0.2	*	*	*	*	*	*
0.3	*	*	*	*	*	*
0.4	*	*	*	*	*	*
0.6		*	*	*	*	*
0.8			*	*	*	*
1.0				*	*	*
1.2					*	*
1.4						*

1 Not tested at temperatures above 100°F.
2 Not tested at temperatures above 120°F.
* Indicates test.
Blank indicates no test.

Figure 11 describes the fundamental operating characteristics at a nominal temperature and waste pressure of 100°F and 5 PSIA (27,000 Ft altitude). The trends depicted in Figure 11 are typical of all known membrane systems. Note that as flow is increased at constant pressure, the oxygen concentration and

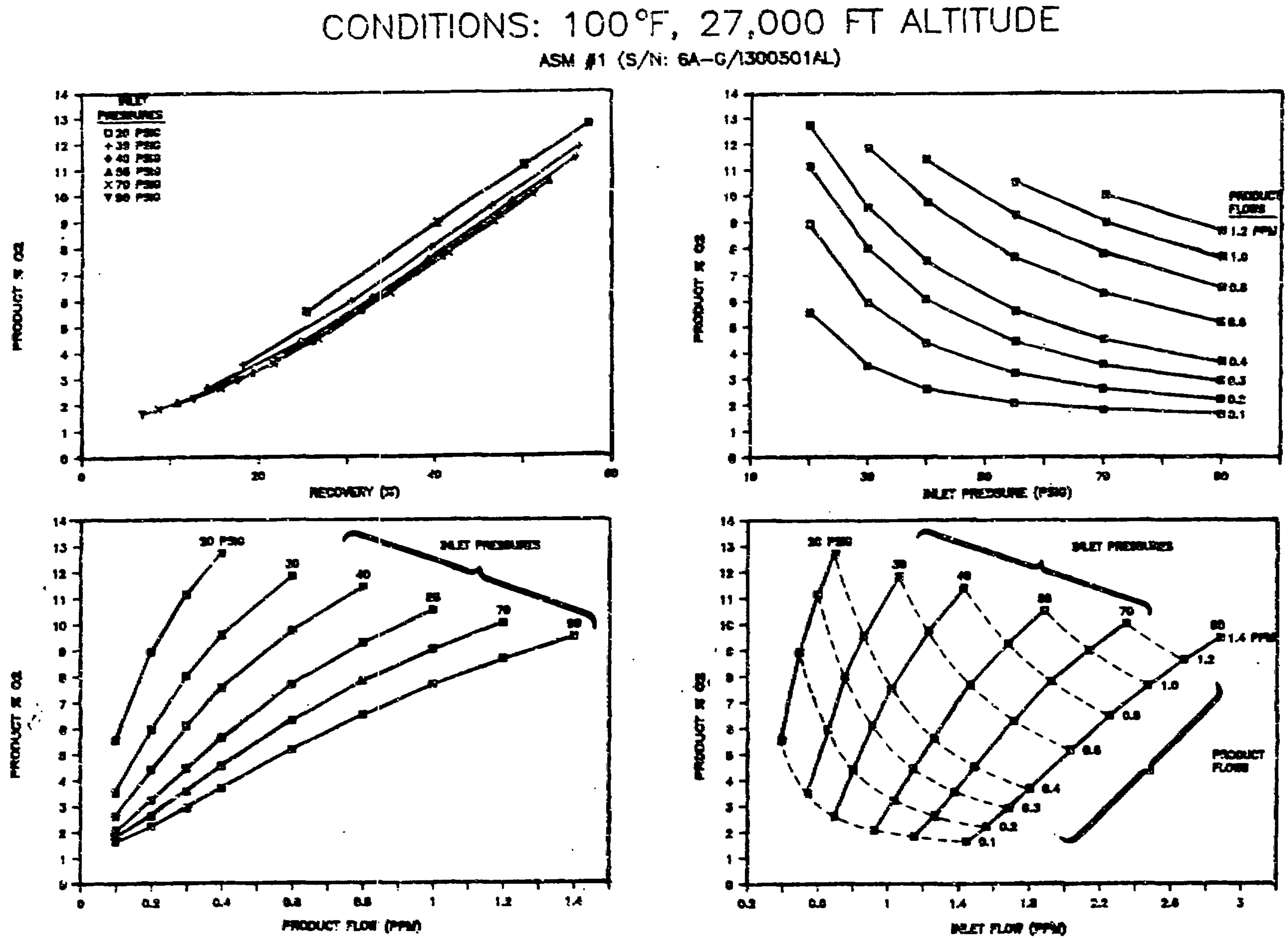


Figure 11. A/G Technology ASM Operating Characteristics

recovery increase. Increasing inlet pressure while holding product flow constant will lower the oxygen concentration significantly but with diminishing effect at higher pressures.

Figure 12 describes the effect of varying altitude or waste pressure at the nominal operating conditions of 100°F and 55 PSIG inlet pressure. Note that for constant product flow, the effect of operating at a higher altitude (i.e. lower waste pressure) is to reduce the oxygen concentration while leaving the recovery essentially unchanged. If product $\%O_2$ is held constant, both product flow and recovery increase with altitude, meaning that higher altitude operation has a purely positive impact on ASM performance.

The effect of increasing temperature while holding inlet pressure, altitude and oxygen concentration constant is shown in Figure 13. Increasing temperatures have a negative impact on recovery; the recovery steadily declines as the temperature increases. However, the effect of temperature on flow capacity is not as clear. Figure 13 suggests an optimum temperature for each oxygen concentration; the higher the $\%O_2$, the higher the optimum temperature. Since testing was limited to 120°F for ASM #1, the optimum temperature for the higher oxygen concentrations could not be determined. Temperature then is seen to have both a positive and negative effect on performance by improving flow capacity while reducing the recovery.

It is difficult to completely describe the performance of the ASM in a simple graphical manner when two dependent and four independent variables are involved. For that reason, the mathematical performance model presented in Section 5.1 has been found to be very useful. For example, using only the test data points, if the effect of altitude on product flow is desired at a constant oxygen concentration, the test data must be cross plotted and interpolated, a cumbersome task. The use of the performance model in Section 5.1 makes such an analysis considerably easier.

A limited performance map was obtained for the second ASM (planned as a spare) since the objective was only to verify that it performed on a par with the first. Since both ASMs were nearly identical, a thorough mapping of the second ASM was unnecessary. The detailed results for ASM #2 are also included in

CONDITIONS: 100°F, 55 PSIG

ASM #1 (S/N: 6A-G/1300501AL)

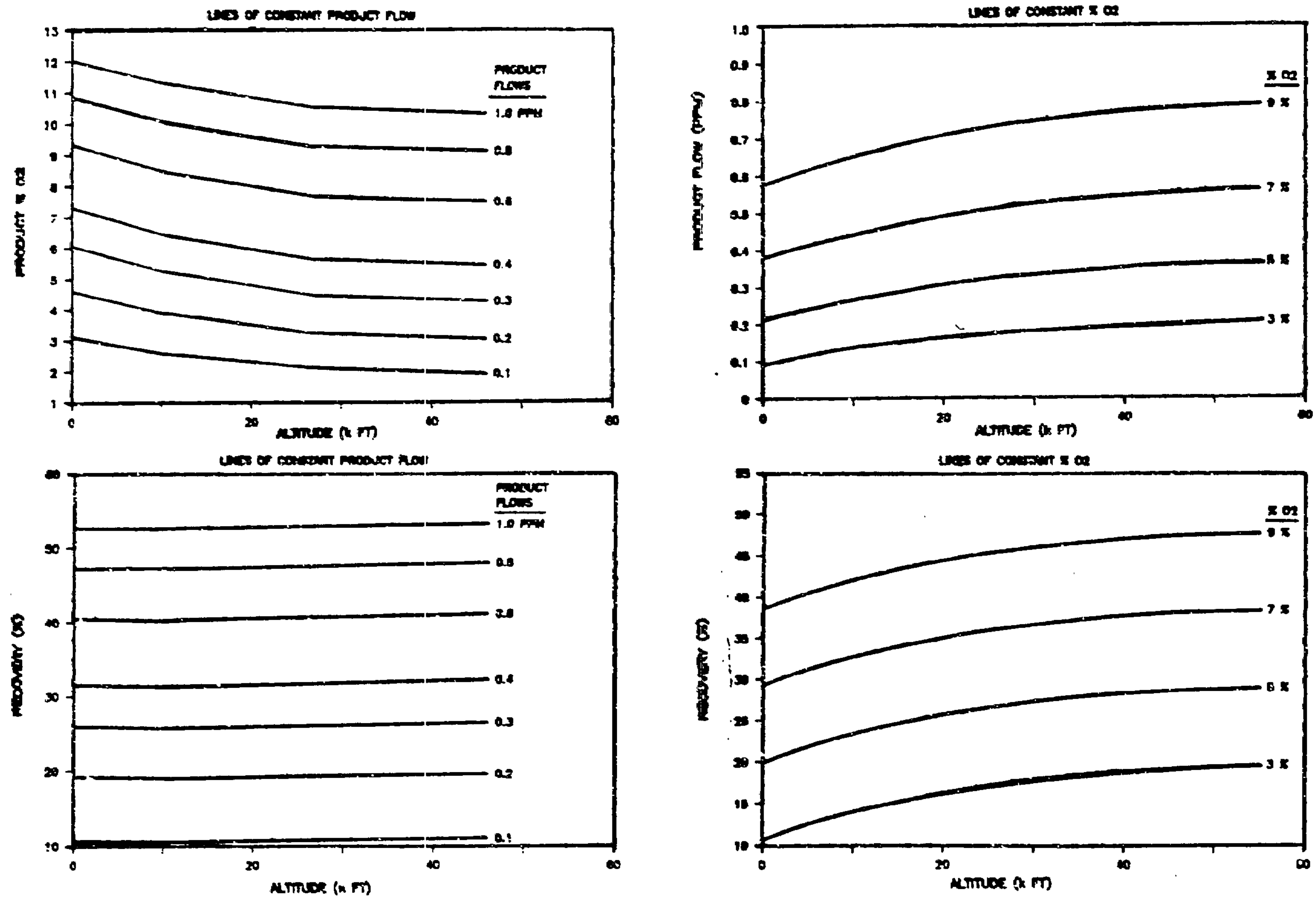


Figure 12 . Effect of Altitude on A/G Performance

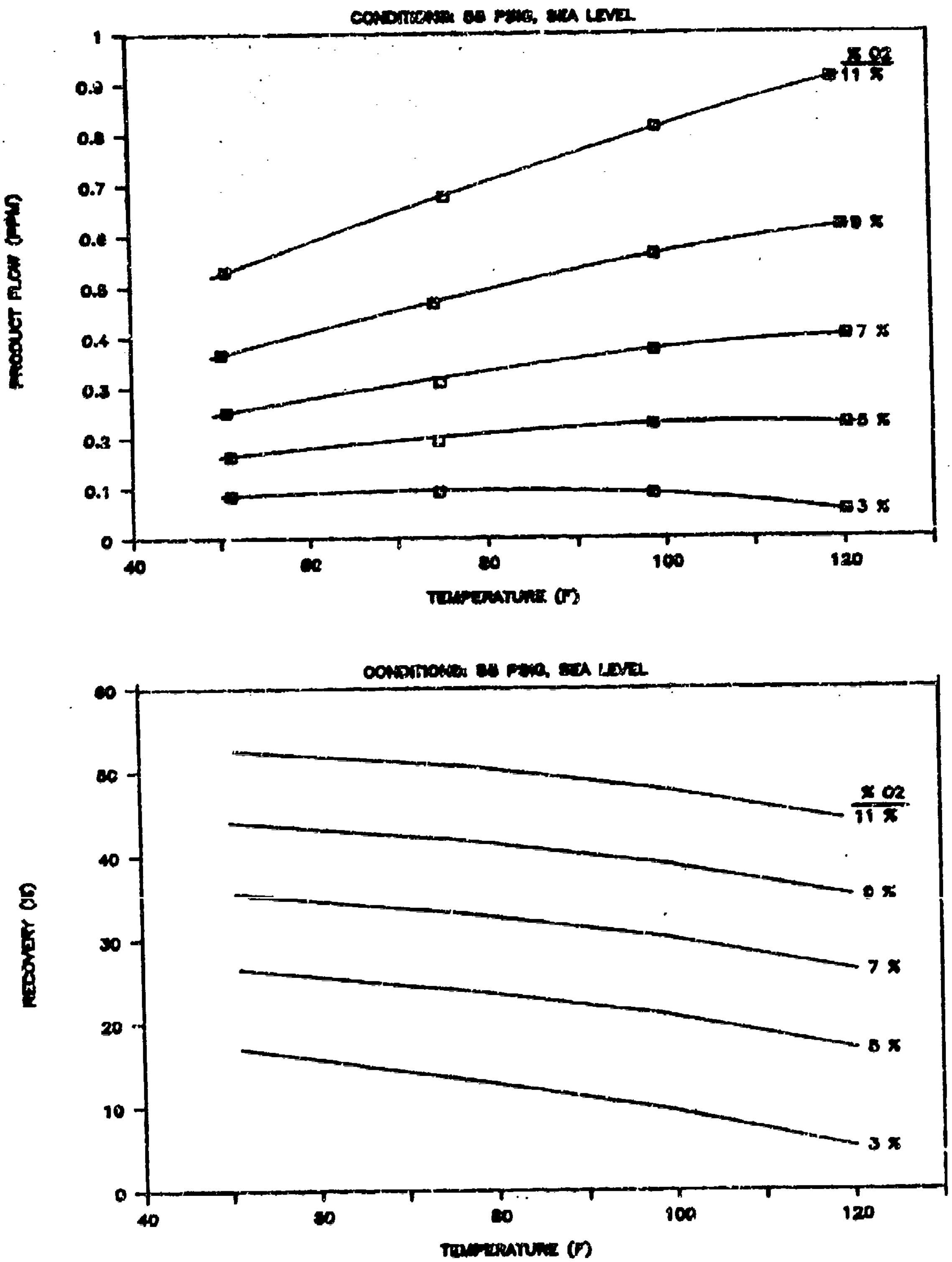
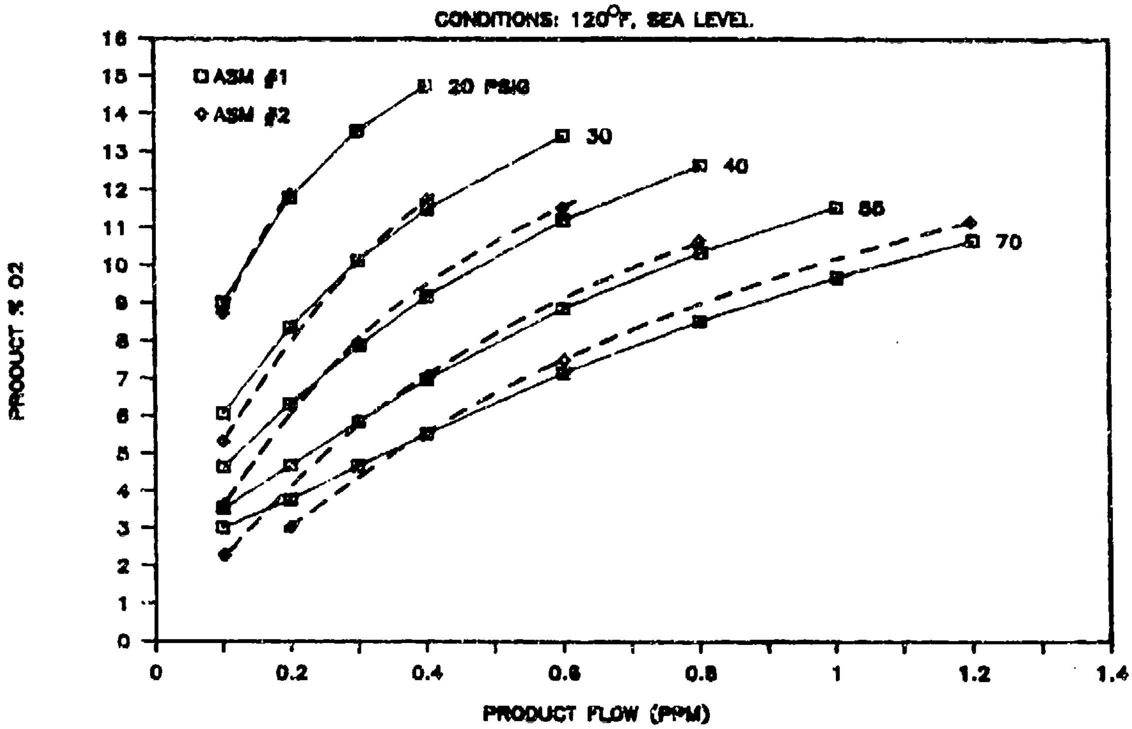


Figure 13. Effect of Temperature on A/G Performance



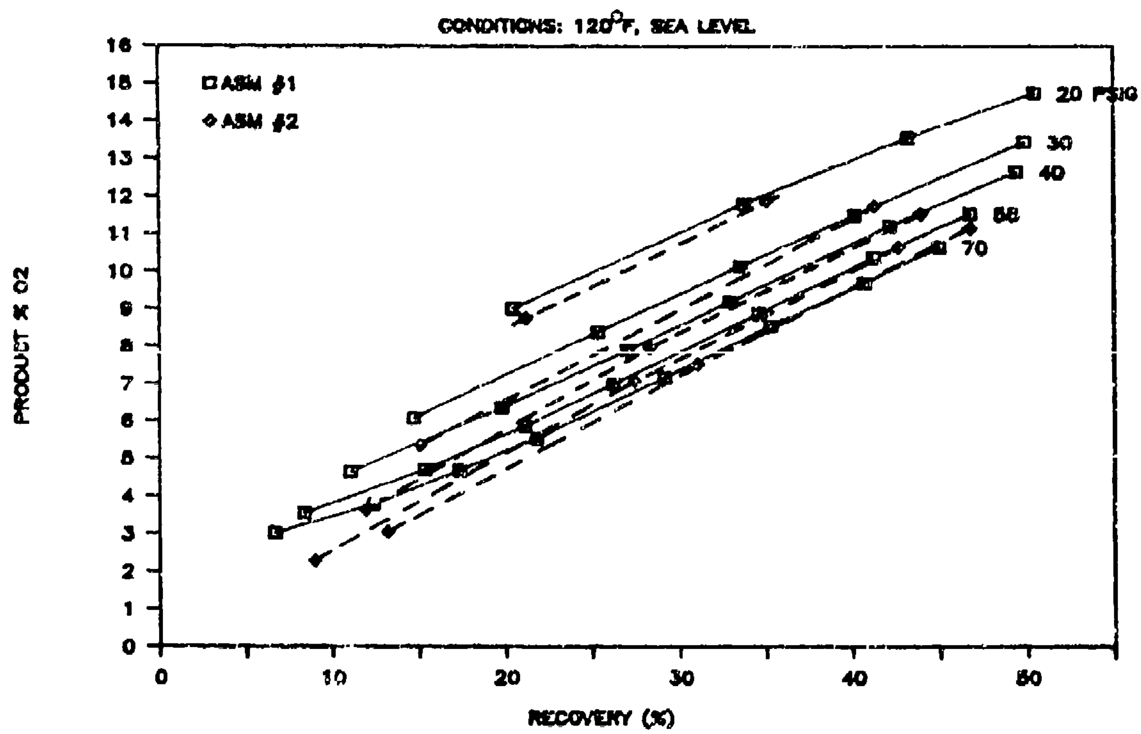


Figure 14 . Comparision of A/G ASM #1 and #2

Appendix D in both graphical and tabular form along with those for ASM #1. An initial comparison of the two A/G units is made in Figure 14 and shows performance to be similar but with some detectable differences. At O_2 concentrations above about 7 percent, ASM #2 is slightly less productive. However, at O_2 concentrations below 7 percent, ASM #2 shows improved performance over ASM #1. This is clearer in Figure 15 which shows the ratio of productivity (#2/#1 product flows) versus $\%O_2$. Note that at the lower O_2 concentrations (in the three $\%O_2$ range), the productivity of ASM #2 is significantly greater than that of ASM #1.

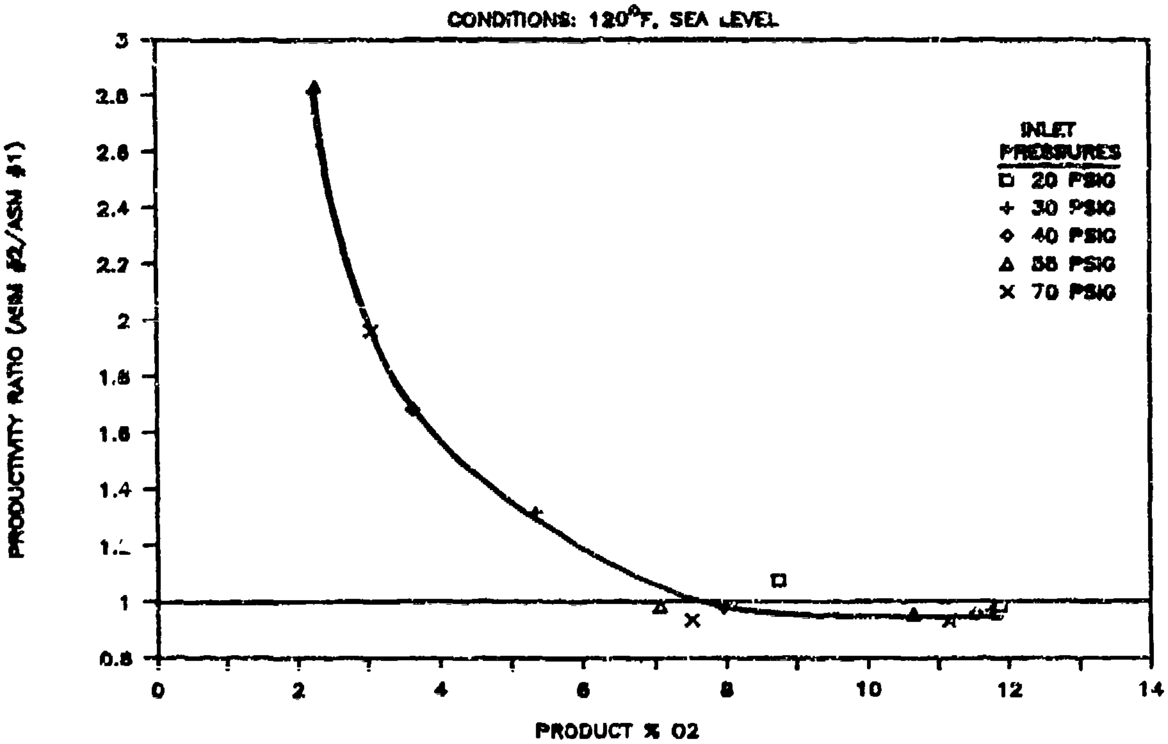


Figure 15. A/G ASM #2 Versus #1 Productivity Ratio

4.1.2 Permea Performance Envelope Test Results

The test matrix used for the Permea ASM (Table 10) indicates the combinations of temperature, waste pressure, inlet pressure and product flow actually tested. The detailed and complete results of the performance envelope tests, in both graphical and tabular form, are included in Appendix E. However, selected results are also presented here in graphical form.

Table 10. Permea Performance Envelope Test Matrix

Temp/waste pres combinations

Waste pres (psia)	Temperature (°F)			
	120	150	175	200
14.7	*	*	*	*
10.0	*			
5.0	*	*	*	*
2.0	*			

* Indicates tests at pres/flow combinations shown at right.

Blank indicates no test.

Pres/NEA flow combinations

NEA flow (ppm)	Inlet pressure (psig)				
	20	30	45	65	90
0.025	*	*	*	*	*
0.050	*	*	*	*	*
0.075		*	*	*	*
0.100			*	*	*
0.125				*	*
0.150					*

* Indicates test.
Blank indicates no test.

Figure 16 describes the fundamental operating characteristics at a nominal temperature and waste pressure of 200°F and 5 PSIA (27,000 Ft altitude). The trends depicted in Figure 16 are similar to those of the A/G unit and are again typical of all membrane systems. Note that as flow is increased at constant pressure, the oxygen concentration and recovery also increase. Increasing inlet pressure while holding product flow constant will lower the oxygen concentration significantly but with diminishing effect at higher pressures. Although the Permea ASM could have been operated at higher pressures, test set- up limitations precluded this.

Figure 17 describes the effects of varying altitude or waste pressure at the nominal operating conditions of 120°F and 65 PSIG. Note that for constant product flow, the effect of operating at a higher altitude (i.e. lower waste pressure) is to reduce the oxygen concentration while leaving the recovery

CONDITIONS: 200°F, 27,000 FT ALTITUDE

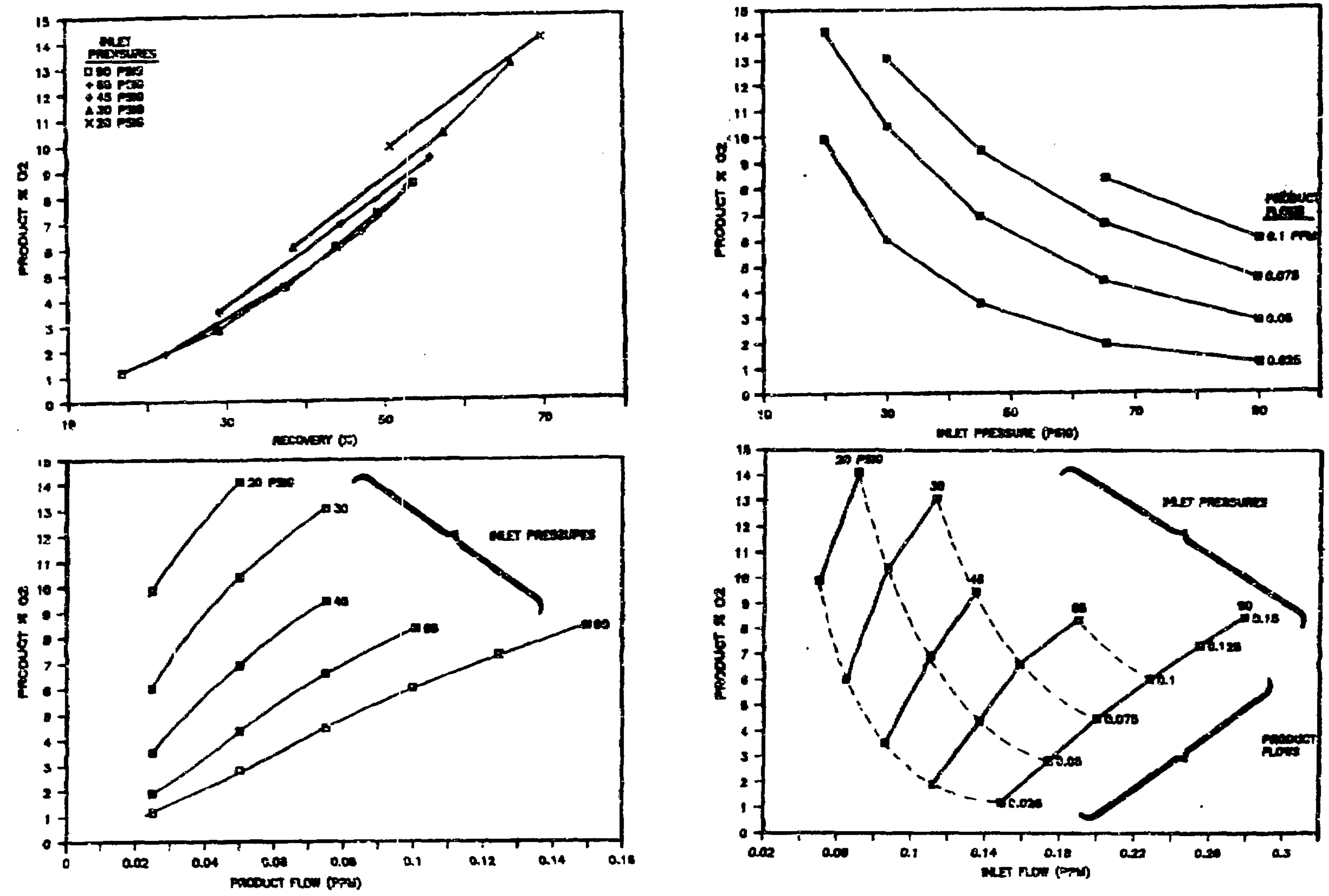


Figure 16. Permea ASM Operating Characteristics

CONDITIONS: 120°F, 65 PSIG

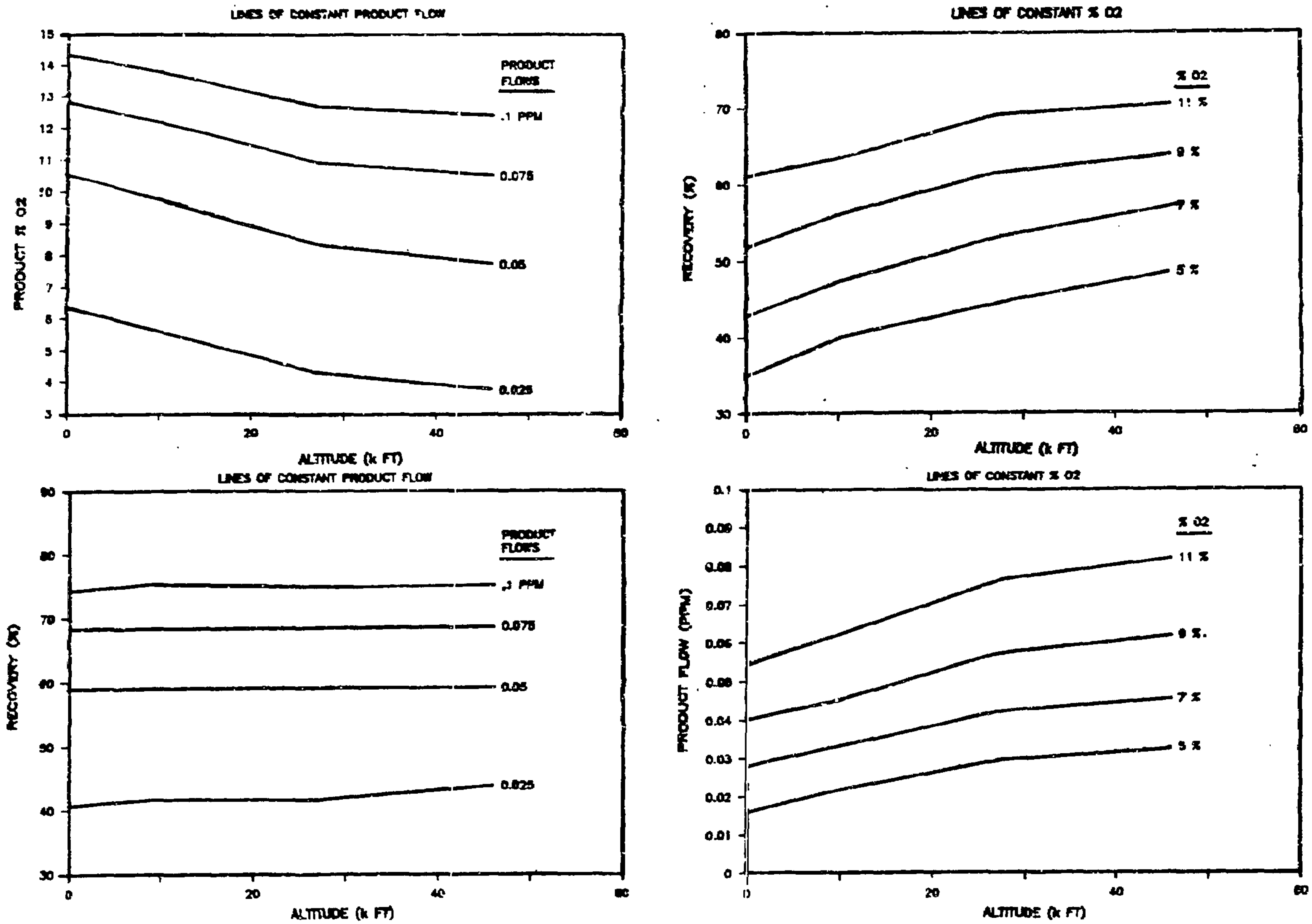


Figure 17. Effect of Altitude on Permea Performance

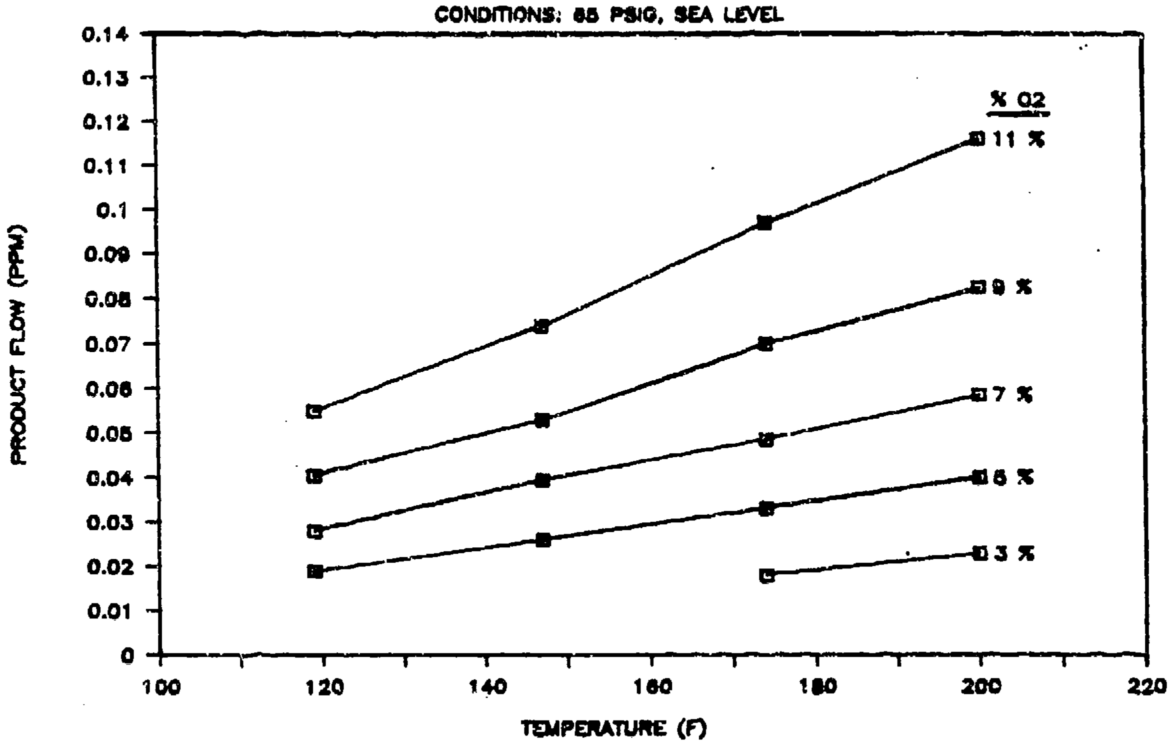
essentially unchanged. If product $\%O_2$ is held constant, both product flow and recovery increase with altitude, meaning that higher altitude operation has a purely positive impact on ASM performance.

The effect of increasing the temperature of the Permea ASM while holding inlet pressure, altitude and oxygen concentration constant is shown in Figure 18. Note that the effect on recovery is for the most part negative; with the recovery again showing a slight but steady decline as temperature is increased. Note that some of the data at 200°F seem to reverse this trend. This is likely due to flow meter inaccuracies and the fact that recoveries at the lower temperatures are estimated (see Appendix F). In any case, the decrease in recovery as temperature is increased appears to be relatively slight. However, the effect of temperature (within the range tested) on flow capacity is clearly positive and produces a significant increase. Temperature then is seen to have both a positive and negative effect on performance by improving flow capacity while reducing the recovery. Unlike the A/G unit, Figure 18 does not suggest an optimum temperature for each oxygen concentration; it appears that higher temperatures will deliver increased flow at any percentO_2 of interest for OBIGGS applications. Testing was limited to 200°F during the Permea performance envelope testing although the performance was evaluated at much higher temperatures at the conclusion of the test program and these results are discussed in detail in Section 4.8.

4.2 Endurance Testing

Both the A/G Technology and Permea ASMs were evaluated over a total of at least 2000 hours while operating at a pressure and temperature near their allowable upper limits. The endurance tests established whether a performance degradation can be expected as a function of operating hours. During endurance testing, the ASMs were operated continuously (24 hours/day, 7 days/week) while periodically (at least once each weekday), performance was carefully measured.

The actual endurance testing evolved from initial plans of 500 hours on only one A/G unit to more than 2000 hours on both the A/G and Permea units. First, 500 hours were accumulated on the A/G ASM #1, then 500 hours on A/G ASM #2 and finally the A/G ASM #2 along with the Permea unit were tested out to 2000 hours.



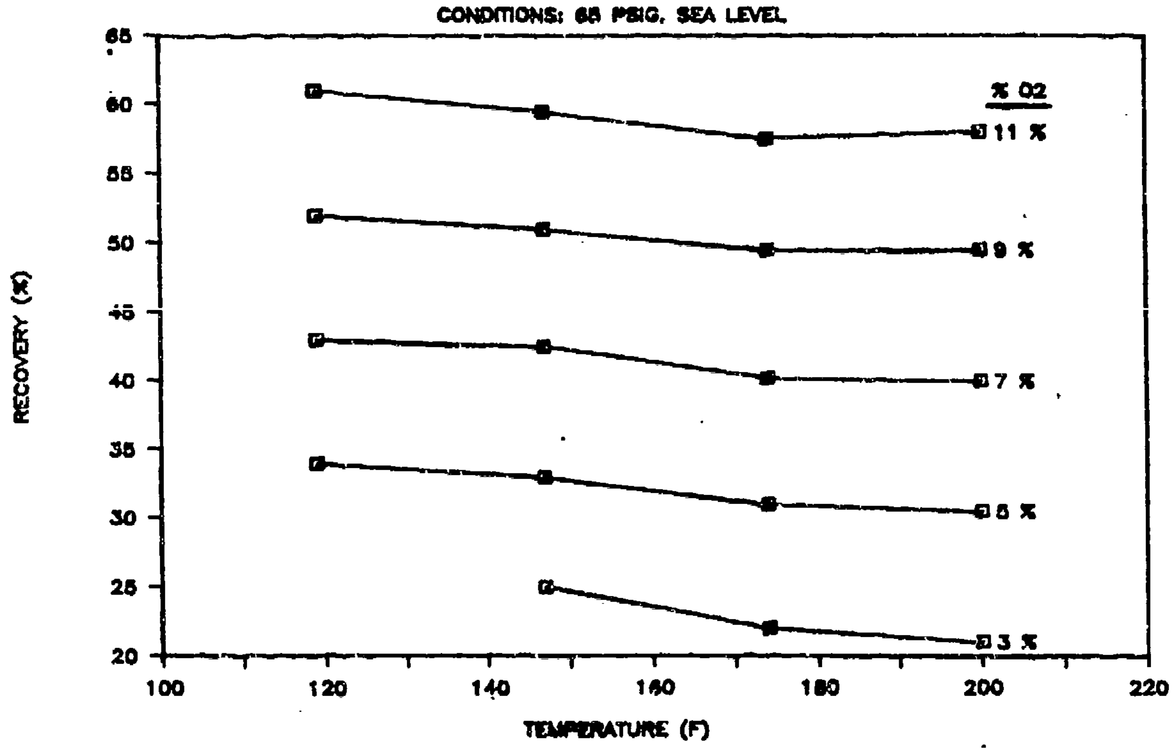


Figure 18. Effect of Temperature on Permea Performance

The endurance tests that occurred after the first 500 Hours were conducted to answer questions raised by the results of the initial tests. Furthermore, additional resources were made available to the program.

While this endurance test was not designed to yield "lifetime" as a function of pressure and temperature, nor last for 10,000 hours (rough target lifetime), the testing was adequate to reveal any serious lifetime problems.

The endurance testing was originally intended to be performed with "clean air" on the assumption that the facility air was free of any significant contaminants. However, it was later found that the inlet air contained oil vapor contaminants (not particulates or aerosol) in significant quantities. In addition, liquid oil was accidentally introduced into the A/G ASM #2 in the middle of the 2000 hour run. These facts combined to yield a test that was a combination endurance/contaminant test.

4.2.1 A/G Technology Endurance Test Results

During all of the A/G Technology endurance testing, the unit was operated at 60 PSIG, 120°F, S.L., and 9 percent O_2. Figure 19 summarizes the results of all phases of the endurance testing as percent change in "productivity" (or how much product flow could be produced at specific conditions) versus total cumulative test time.

Note that data for both A/G units are presented in Figure 19. Endurance testing was first begun with ASM #1 and lasted 500 hours without the inlet carbon filter. When the obvious 6 percent degradation was suspected to be caused by the inlet air vapor contamination, a single carbon filter was installed on the inlet to the ASM and ASM #1 was tested for another 250 hours with no apparent degradation from 500 to 750 hours as can be seen in Figure 19.

In order to prove that a previously untested ASM will not degrade on what was assumed to then be clean, carbon filtered air, ASM #2 was tested for 500 hours and showed a significant improvement over ASM #1 (Figure 19). While this test confirmed that the originally observed degradation with ASM #1 was in large part due to the oil vapor contaminants in the inlet air, close inspection of the data in Figure 19 will reveal that ASM #2 still exhibited a slight tendency to lose performance at the rate of 2 percent over the first 1000 hours.

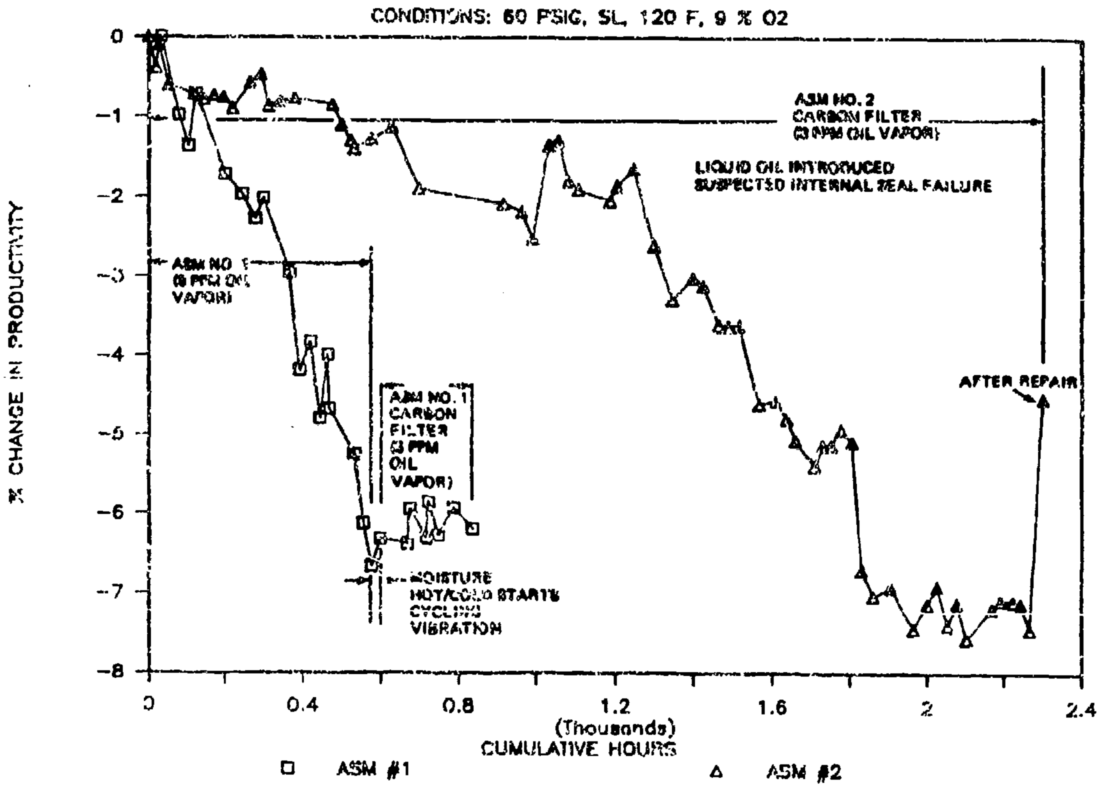


Figure 19. A/G Endurance Test Results Summary

ASM #2 endurance testing was then later extended past 2000 total hours. However, as can be seen in Figure 19, at approximately 1000 hours the rate of degradation increased markedly to 5 percent per 1000 hours. This was at first attributed to a small quantity of liquid oil that was accidentally introduced into the ASM inlet at 952 hours. However, when the ASM was returned to A/G Technology, a crack was discovered in an ASM internal seal that allowed leakage of product gas directly into the waste gas. The data, which show waste flow increasing and recovery decreasing by roughly the same amount, tend to confirm the development of a crack. ASM #2 was repaired by A/G Technology and returned for retest. The repairs consisted of end cap modifications to incorporate A/G's latest construction techniques.

The final data point shown in Figure 19 indicates the retested performance improved but did not fully return to initial levels. Considering the final data point after repair, it appears that the majority of performance decline observed in the second half of the ASM #2 endurance test was due to an ASM internal tube sheet design flaw and not fiber degradation. However, using the final after repair data point, the ASM still exhibited a performance degradation rate of roughly 2 percent per 1000 hours.

In Figures 20 and 21 more detailed data are presented for ASM #1 and ASM #2 respectively in the form of the percent change in product flow, waste flow and recovery, from initial values. Note that in addition to the steady decrease in productivity, waste flow and to a lesser extent recovery, also decreased. The two ASMs differed in that #1 exhibited about a 3 percent drop in recovery while #2 (based on the final after repair data point) changed less than 1 percent. In general, the degradation observed with both ASMs can be characterized as a decrease in effective size.

Inspection of ASM #1 after the endurance test revealed that it had a noticeable odor (a new ASM has no detectable odor) characteristic of the air supply. This suggested that some form of inlet air contamination was present and actually "depositing" on the fibers. This would explain the apparent degradation. A/G Technology has indicated that they have operated similar fibers under approximately the same conditions for several thousand hours with no measurable change in performance (See Appendix A). The contamination was measured using a total hydrocarbon analyzer and found to be approximately 9 PPM and 3 PPM (Parts Per Million) upstream and downstream of the carbon filter respectively. Appendix G contains a detailed discussion of this contamination as well as how it relates to actual bleed air contaminants. Note that the effect contaminants on ASMs will probably be different on stored gas versus demand OBIGGS (see Section 6.2).

4.2.2 Permea Endurance Test Results

During all the Permea endurance testing, the unit was operated at 90 PSIG, 200°F, S.L., and 9 percent O_2. Figure 22 summarizes the results of the endurance testing as percent change in "productivity" (or how much product flow could be produced at specific conditions) versus total cumulative test time. Note that the Permea unit lost roughly 13 percent of its productivity

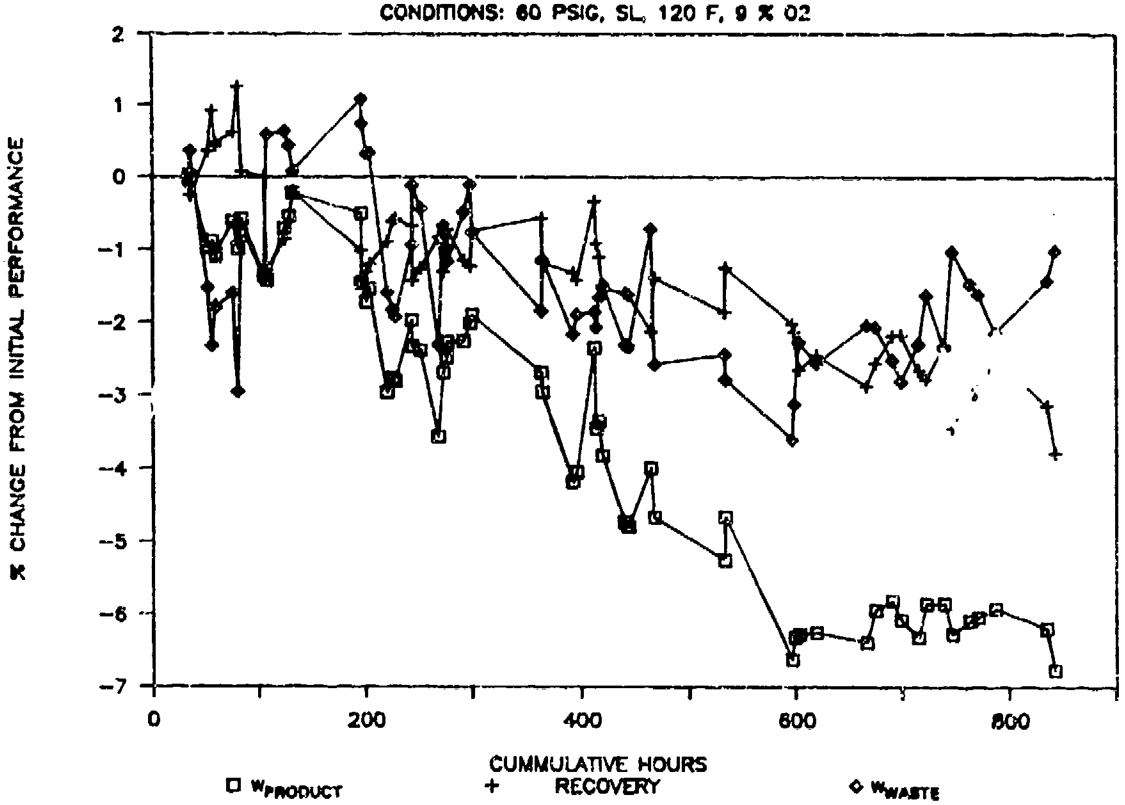


Figure 20. A/G ASM No. 1 Endurance Test Results

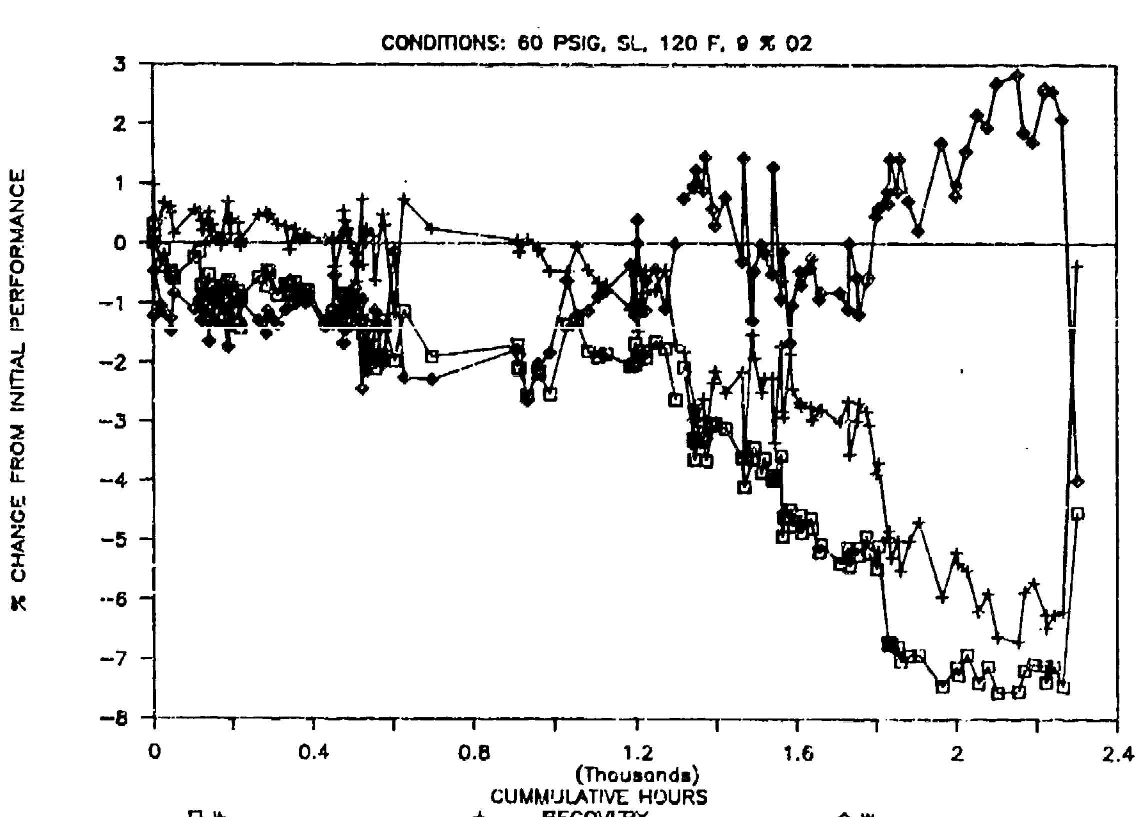
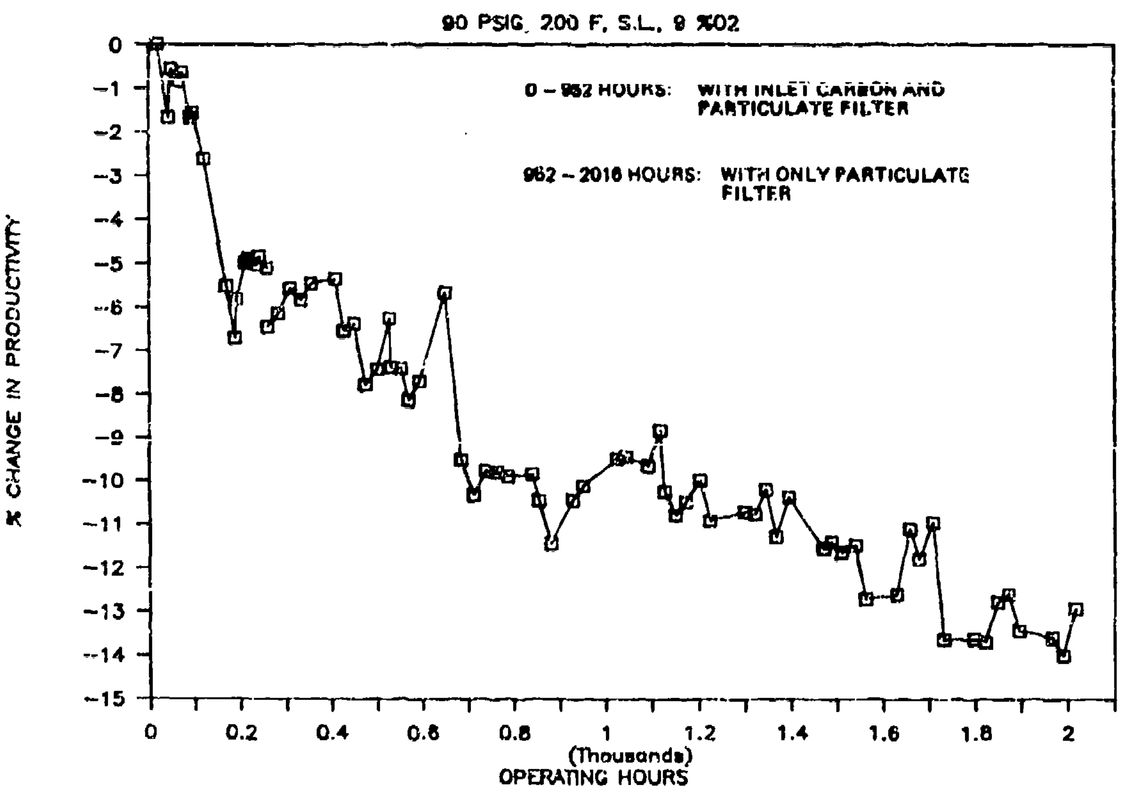


Figure 21. A/G ASM No. 2 Endurance Test Results

over the 2000 hour test with the majority of the loss occurring in the first 200 to 300 hours.

The first 952 hours of the Permea endurance were accumulated with an inlet carbon filter to remove the oil vapor contamination and allow data to be collected with "clean air" first. However, the final 1064 hours were accumulated without the inlet carbon filter (only a particulate filter) to see what effect the oil vapor would have on degradation. The results indicated that the oil vapor caused no noticeable increase in the rate of degradation, and in fact the rate of performance loss appears to have actually decreased during the second half of the testing. The Permea ASM does not seem to be sensitive to the type of oil vapor contaminants encountered in the inlet air used in this test.



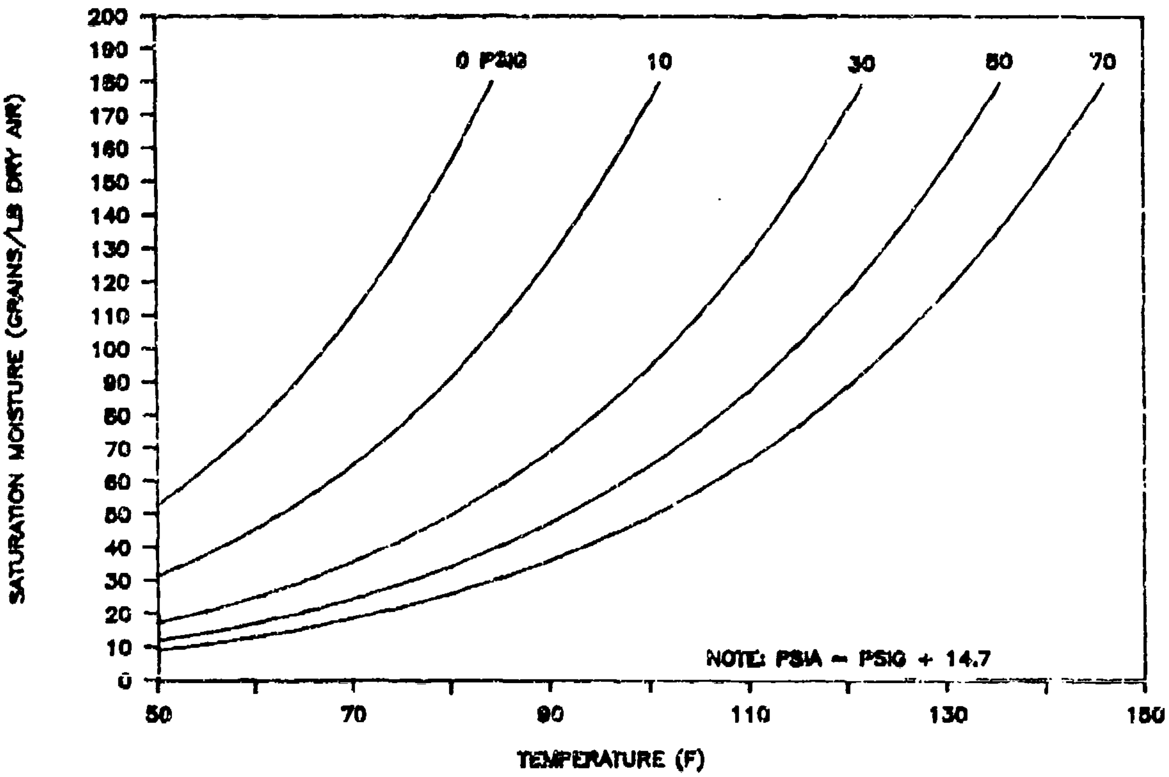
The recovery did not change significantly considering the limitations of the flow meters used. In general, recovery fluctuated between 48 and 49 percent and did not exhibit any trend as did the productivity. As described in Section 2.4, the Permea ASM was not operated in a constant temperature environment. Rather it was simply well insulated and operated with a constant inlet temperature. Variations in ambient temperature caused slight changes in ASM temperature which are considered responsible for the minor productivity fluctuations shown in the Figure 22 productivity data as well as the 1 percent fluctuations in recovery.

4.3 Moisture Sensitivity

The moisture sensitivity testing was performed only with the A/G Technology ASM. Moisture levels up to 180 grains/Lb of dry air were tested while the ASM was evaluated for performance degradation during and after the moisture tests. Figure 23 shows that 180 grains/Lb is the highest moisture level expected in flight as per MIL-E-38453A. The ASM operating conditions were 30 PSIG, 120°F, S.L., and 9 percent O_2. The ASM was operated at the rather low pressure of 30 PSIG in order to achieve the 180 grain moisture content at 120°F. The reason for this can be seen in Figure 23 which shows saturation moisture levels as a function of pressure and temperature. The moisture levels were measured by taking samples at the ASM inlet, which was downstream of the coalescer filter.

Figure 24 shows the effect of inlet dew point on the performance of the A/G ASM as moisture levels are varied from initially dry to fully saturated at 180 grains and then back to dry conditions. Note that the performance is affected by inlet moisture but returns to initial levels when dry conditions are re-established. The productivity is decreased during the high dew point conditions while recovery (not shown in Figure 24) remained unchanged. An explanation for this sensitivity is presented in Section 5.6.

Data were also obtained on the moisture separation factor (i.e., the ratio of moisture in the NEA to that in the inlet air). The moisture separating efficiency data are valuable for stored gas OBIGGS applications where the water condensate problem will have to be addressed in the high pressure compressor. The data obtained with both inlet and product dew point measurements are presented in Table 11. Note that the dew points were measured at the line pressures of the inlet and product gases and are termed pressure dew points. In



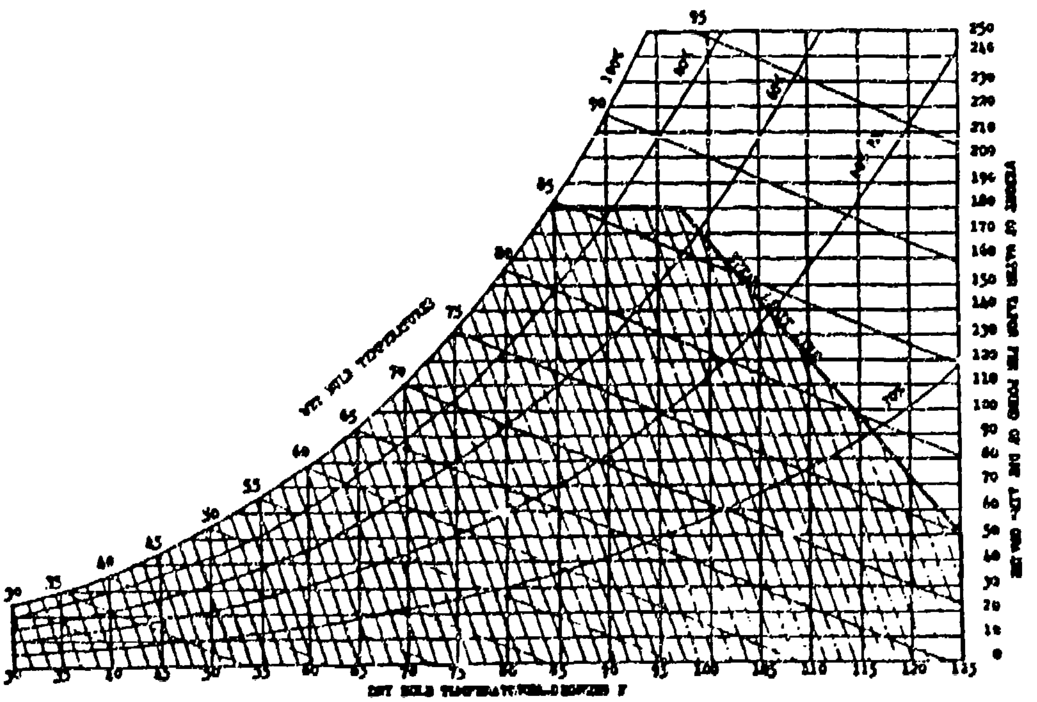


Figure 23. Expected Inlet Moisture Levels

general, the normal operating ranges for the A/G ASM will yield relatively dry product gas even under saturated inlet conditions. Further analysis of the moisture separating performance is presented in Section 5.7.

The test procedure used in the moisture tests amounted to adding controlled amounts of steam to the inlet air until the desired dew point was obtained. Control of the inlet dew point was complicated by the fact that the moisture analyzer required roughly a minute to stabilize while steam pressure fluctuated.

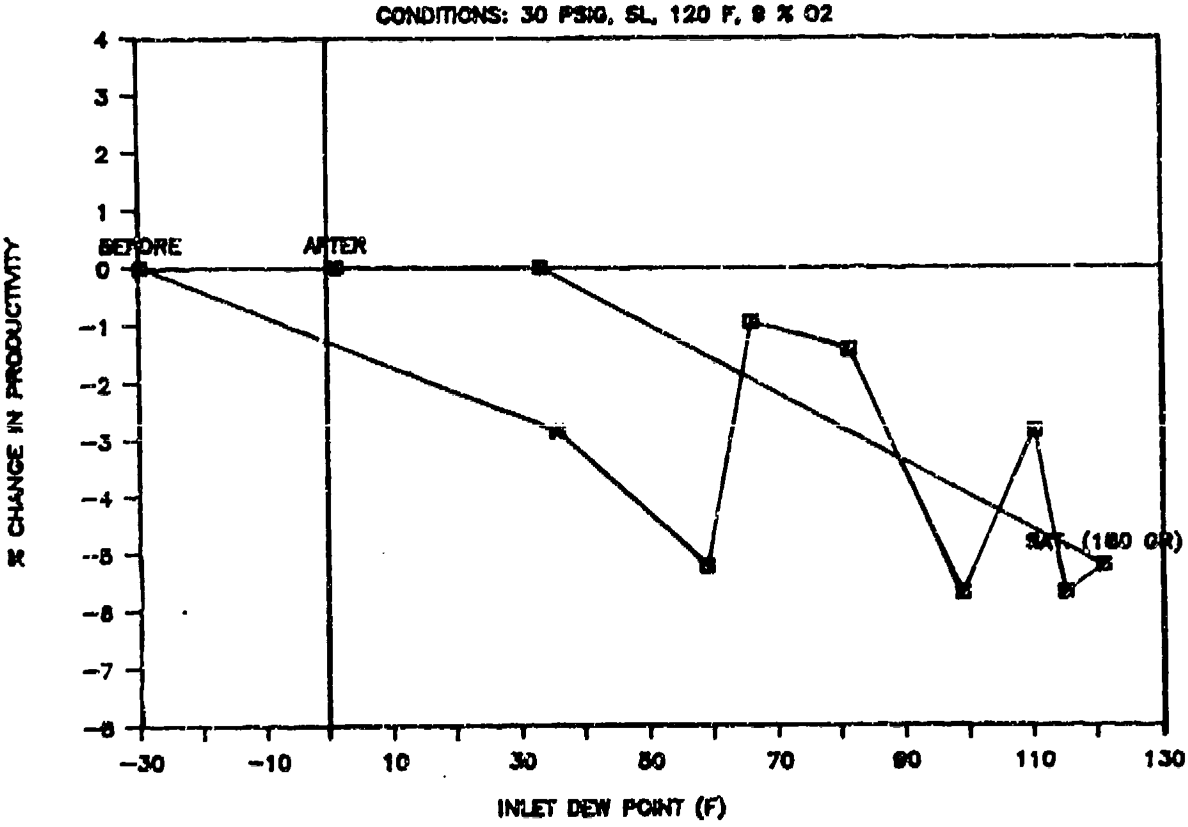


Figure 24. A/G Moisture Sensitivity

Due to the test method mandated by only one moisture analyzer (the analyzer had to be switched between the inlet and NEA flows), the accuracy of the moisture separation test results was adversely affected. The test procedure required that stable dew points first be established in the inlet air and then the analyzer was switched to the NEA flow stream. The time required to obtain stable readings from the moisture analyzer, along with large swings in dew point (often on the order of 100°F) meant that some "drift" in the inlet moisture reading was unavoidable. The drift is estimated to have caused less than a 3°F dew point measurement error. In addition, the limited range of the dew point meter prevented the moisture separation factor at certain conditions from being measured entirely. The test would have benefited from the use of a second analyzer so that a dedicated analyzer could continuously monitor both inlet and NEA flow simultaneously. However, this moisture separation data should be adequate for OBIGGS design purposes.

Table 11. A/G Moisture Separation Data

Inlet pressure (psig)	Waste pressure (psia)	T-ASM (°F)	Product		Recovery (%)	Pressure dew points	
			Flow (ppm)	Oxygen (%O_2)		Inlet (°F)	Product (°F)
30.13	14.63	121.3	0.205	8.97	26.62	35.9	-22.4
30.07	14.63	122.5	0.209	9.04	26.78	66.1	-4.9
30.08	14.61	122.7	0.208	8.97	26.33	81.5	12.1
30.17	14.59	122.7	0.208	8.96	26.61	82.0	12.1
29.97	14.52	121.7	0.199	9.01	26.35	99.1	17.4
30.06	14.57	123.2	0.205	9.01	26.91	110.4	29.6
29.89	14.54	122.8	0.199	9.05	27.03	115.1	30.5
29.86	14.56	123.4	0.200	8.97	26.66	121.1	34.2
60.31	14.77	121.5	0.759	9.74	39.47	99.8	-2.6
39.88	10.01	121.8	0.518	10.03	40.78	105.4	1.1
40.24	10.01	122.4	0.517	9.94	40.15	107.9	3.6
30.00	7.48	122.6	0.372	9.90	39.82	111.0	5.8
19.96	5.03	122.8	0.241	9.98	40.29	111.5	7.6
20.10	6.16	123.0	0.157	8.37	30.28	112.1	-2.6
30.01	9.21	122.6	0.233	8.17	29.41	112.4	0.2
30.06	14.57	123.2	0.205	9.01	26.91	110.4	29.6
20.24	14.56	122.7	0.106	9.63	21.51	71.1	20.4
30.00	14.88	121.6	0.154	7.97	21.33	77.3	-3.3
30.05	11.02	121.5	0.267	9.01	31.60	71.8	-9.4
40.04	10.85	121.7	0.263	6.87	24.99	71.6	-33.7
49.99	11.46	121.5	0.337	6.56	25.21	72.3	-30.7
40.04	15.97	122.0	0.528	11.27	40.32	92.2	27.3
30.33	16.06	122.3	0.253	10.18	30.72	89.9	28.1
50.10	11.39	122.0	0.339	6.66	25.59	102.6	-18.3
30.03	15.89	102.2	0.198	9.87	31.31	92.3	30.6
30.11	14.87	101.5	0.111	7.38	20.26	91.6	5.5
30.08	9.16	101.6	0.193	7.73	30.18	91.8	-11.4

4.4 Hot/Cold Start-Up

The hot/cold start-up tests were intended to evaluate ASM performance during a simulated start-up after a cold (-60°F) and hot (+140°F) soak. These tests were performed only with the A/G Technology ASM. This test was designed to determine if any detrimental effects occur from worst case thermal transients and how long before acceptable performance is obtained. Since significant thermal stresses can be expected during these start-up transients, the possibility of cracks occurring can not be eliminated without tests. While performance was expected to be poor at the low temperatures, it is desirable for the time required to reach operating temperature to be as short as possible.

During these tests, the ASM was brought to an initial temperature (no flow) and allowed to equilibrate for several hours while the inlet plumbing was maintained at 100°F to provide the "steepest" temperature change at the ASM inlet during start-up. This was felt to be a "worst case" situation since in an actual airplane environment, a large portion of the inlet plumbing would also be at the initial soak temperature causing a slower rise. At time zero, 100°F inlet air was introduced at 60 PSIG with the product flow preset to yield approximately 7 percent O_2 when the ASM reached final operating temperature. The temperature control for the box was turned off at time zero allowing the box environment to thermally float. This was necessary because a fan was used in the box temperature control and provided a significant amount of convection heat transfer from the ASM case and would not be typical of an airplane compartment. A breakdown of the test variables is included in Table 12.

Table 12. Hot/Cold Start-up Test Conditions

Variable	Hot start I.C.	Hot start Test	Cold start I.C.	Cold start Test
ASM case temp (°F)	140	-	-60	-
BOX temp (°F)	140	-	-60	-
ASM inlet temp (°F)	-	100	-	100
ASM inlet pres (psig)	0	60	0	60
NEA flow (ppm)	0	0.4	-	0.4
Final NEA % O_2	-	7	-	7

Note: I.C. = Initial conditions.
Test = Conditions from time zero.

Neither the hot nor cold start-up tests caused any damage to the ASM or produced any permanent performance degradation. The actual thermal response (inlet and ASM case temperature versus time) during both the hot and cold start-up tests is shown in Figure 25. Note that, in the lower figure, the ASM case temperature lags significantly behind the inlet air temperature for both hot and cold starts. The product percentO_2 for the hot start shown in the upper figure indicates no start-up delay since 140°F is essentially a high but reasonable operating temperature. However, when starting from -60°F, the data indicate that approximately 4 to 5 minutes are required before the ASM is "on condition". This 4 to 5 minute period is much shorter than case temperature profile would suggest, indicating that the fibers warm up much faster than the case.

The inlet flows varied during the start-up tests due to changing fiber temperatures. The final inlet flow (at 100°F) was approximately 1.4 PPM but began as high as 1.8 PPM and as low as 0.6 PPM for the hot and cold start-up conditions respectively.

4.5 On/Off Cycling

The on/off cycling tests were only performed with the A/G Technology ASM. This series of experiments was included as a precaution because of the performance degradation experienced with the DOW permeable membrane unit (Reference 1). There was no preliminary indication that the A/G unit would be sensitive to on/off cycling.

The A/G ASM was subjected to a nominal 1000 on/off cycles with periodic performance checks to monitor potential degradation. The cycle tests were conducted at 60 PSIG, 120°F, Sea Level and 9 percent O_2 with an on/off cycle defined as follows:

- o Open ASM inlet valve.
- o Allow the ASM performance to stabilize (13 seconds).
- o Close the ASM inlet valve.
- o Allow the ASM pressure to bleed down to ambient (4 seconds).
- o Repeat the above steps.

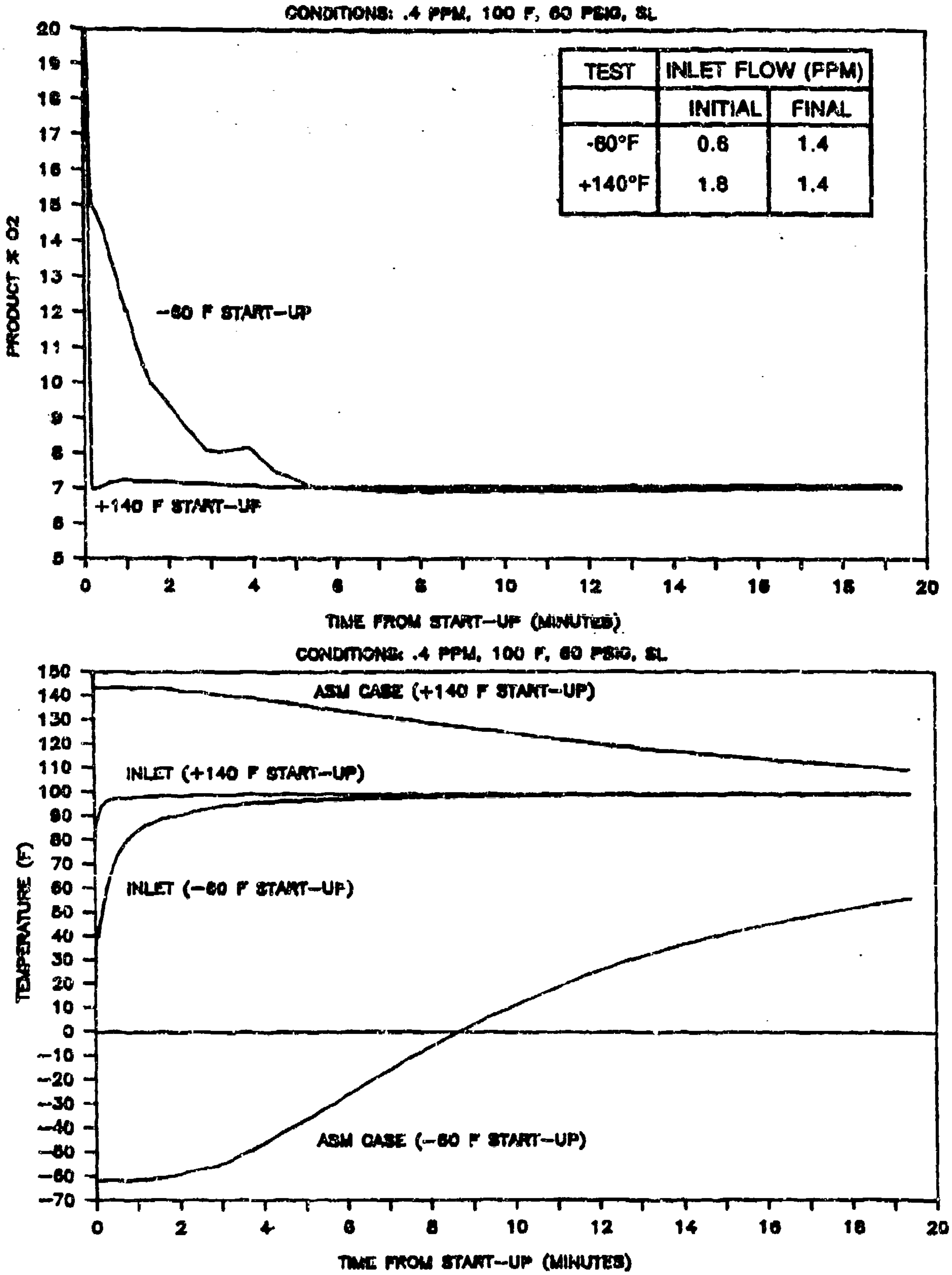


Figure 25. A/G Hot/Cold Start-Up

The ASM inlet pressure over an entire cycle is depicted in Figure 26. This cycle time allowed an average of 210 cycles per hour and permitted the entire 1000 cycle test to be completed in one day.

The inlet valve was an air operated ball valve intentionally located directly in front of the ASM inlet to produce a relatively short pressure rise time. The pressure versus time during the valve opening was measured with a fast response transducer and recording system. The rise time is depicted in Figure 26 and exhibited a time constant of approximately 0.15 second with a relatively steep initial rise (0.5 PSI/Millisecond). The time required to fully open the air operated ball valve was roughly 0.2 second.

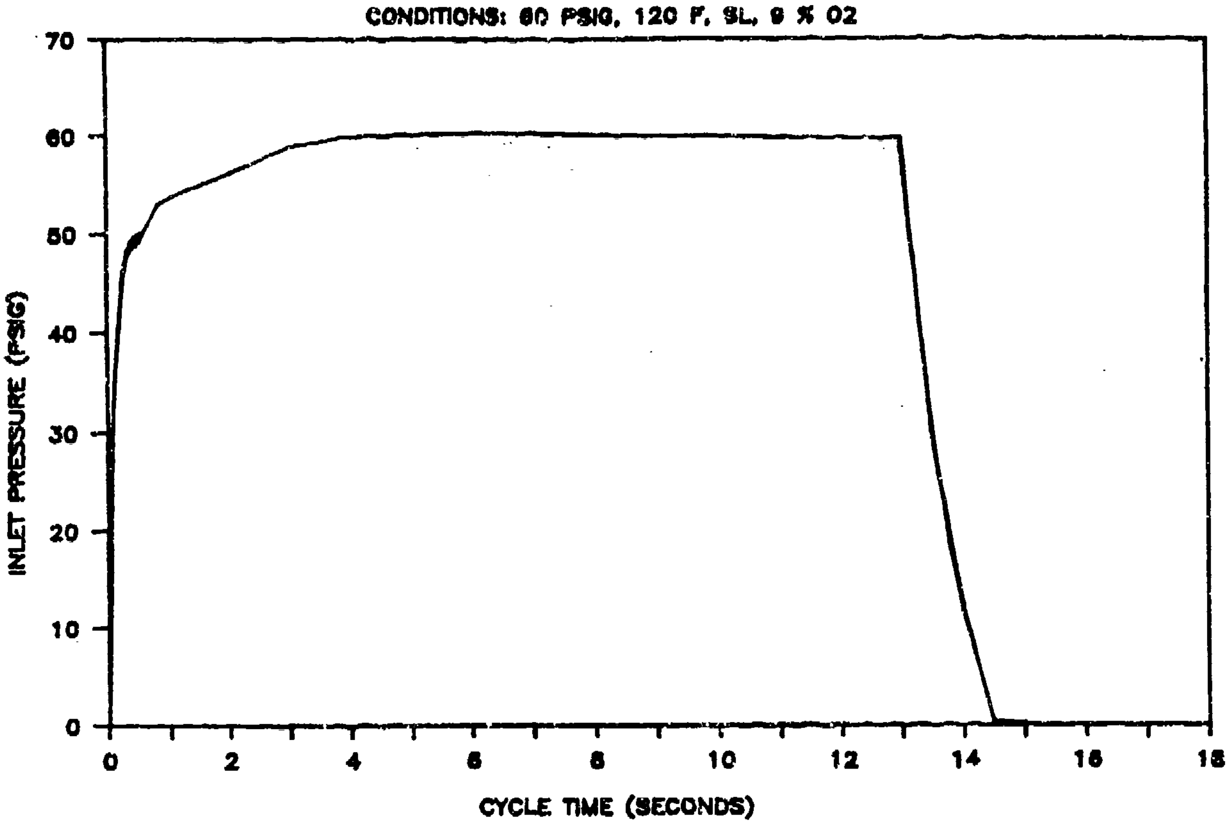
The performance of the A/G unit was measured periodically throughout the cycle testing and results are presented in Table 13. Note that there was no significant change in performance (productivity or recovery) over the entire 1000 cycles.

Table 13. A/G Performance During On/Off Cycle Tests

Total cycles	Product flow (ppm)	Recovery (%)
0	0.664	34.70
50	0.662	34.65
100	0.662	34.51
200	0.663	34.59
500	0.664	34.52
1000	0.664	34.57
Conditions: 60 psig, sea level, 120°F, 9% 0_2		

4.6 Vibration Sensitivity

The vibration test was only performed with the A/G Technology ASM. Since the ASM was relatively small and weighed only 4 pounds, it was practical to perform operational vibration tests (i.e., vibrate while the ASM is pressurized and producing NEA) and thereby assure continuous performance monitoring. This operational vibration test determined if vibration (1) affected performance and (2) caused undesirable mechanical response or damage.



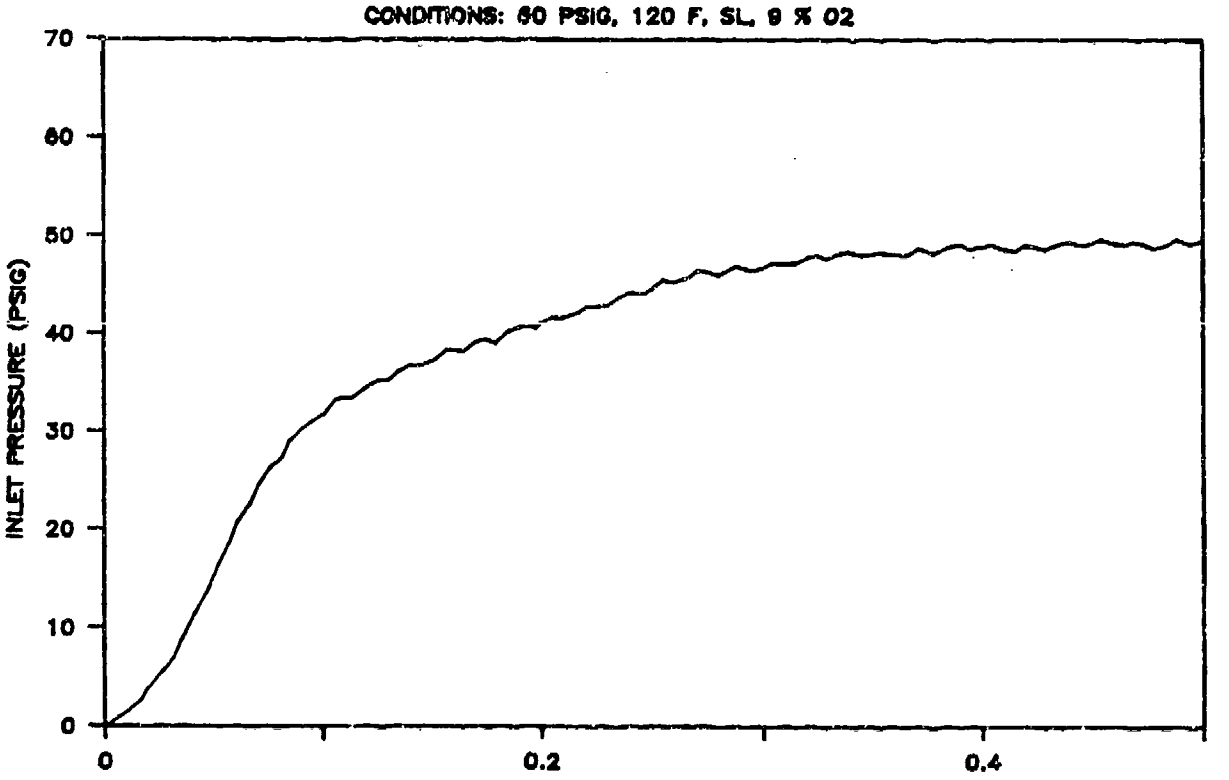


Figure 26. A/G On/Off Cycle

The mechanical response of the ASM was measured by recording the transmittance (ratio of g's measured at the center of the ASM to input g's at the end fitting clamp) as a function of excitation frequency. This identified the resonant frequencies of the ASM and their severity. This vibration test was developmental in nature; the mechanical response of an ASM installed on an airplane may be significantly different. This test was conducted in one axis only, that perpendicular to the longitudinal axis of the ASM.

The vibration frequency/amplitude envelope used for these tests is shown in Table 14. The vibration table was capable of producing only single frequency sinusoidal excitation and did not have random vibration capability. This vibration envelope is specifically for sinusoidal vibration tests and was obtained from MIL-E-5400T, Section 3.2.24.5 which is applicable to equipment designed for installation in jet aircraft. Note in Table 14 that certain frequency ranges are displacement limited while others are acceleration limited. During these tests the vibration equipment could be adjusted to any single frequency between 5 and 2000 Hz at the amplitude specified in Table 14 while the mechanical response or performance was recorded.

Table 14. Vibration Envelope

Frequency (Hz)	Amplitude
5 - 14	100 mills*
14 - 23	1 g
23 - 74	36 mills*
74 - 2000	10 g's

* Displacement (0.001 inches double amplitude)

The results of these vibration tests indicate that the ASM performance was not measurably affected over the entire vibration envelope. Simple visual observation of the ASM and its fibers inside the clear case revealed no apparent mechanical response problems such as obvious fiber movement inside the ASM case at low frequencies.

The transmittance of the ASM versus vibration frequency shown in Figure 27 indicates several points of resonance, the first and most prominent at 100 Hz. This response curve is considered classic up to 300 Hz. The higher resonances may be attributed to individual mechanical parts in this particular test apparatus, including the accelerometers themselves. A near final design is normally tested before significance is given to these higher frequency resonances.

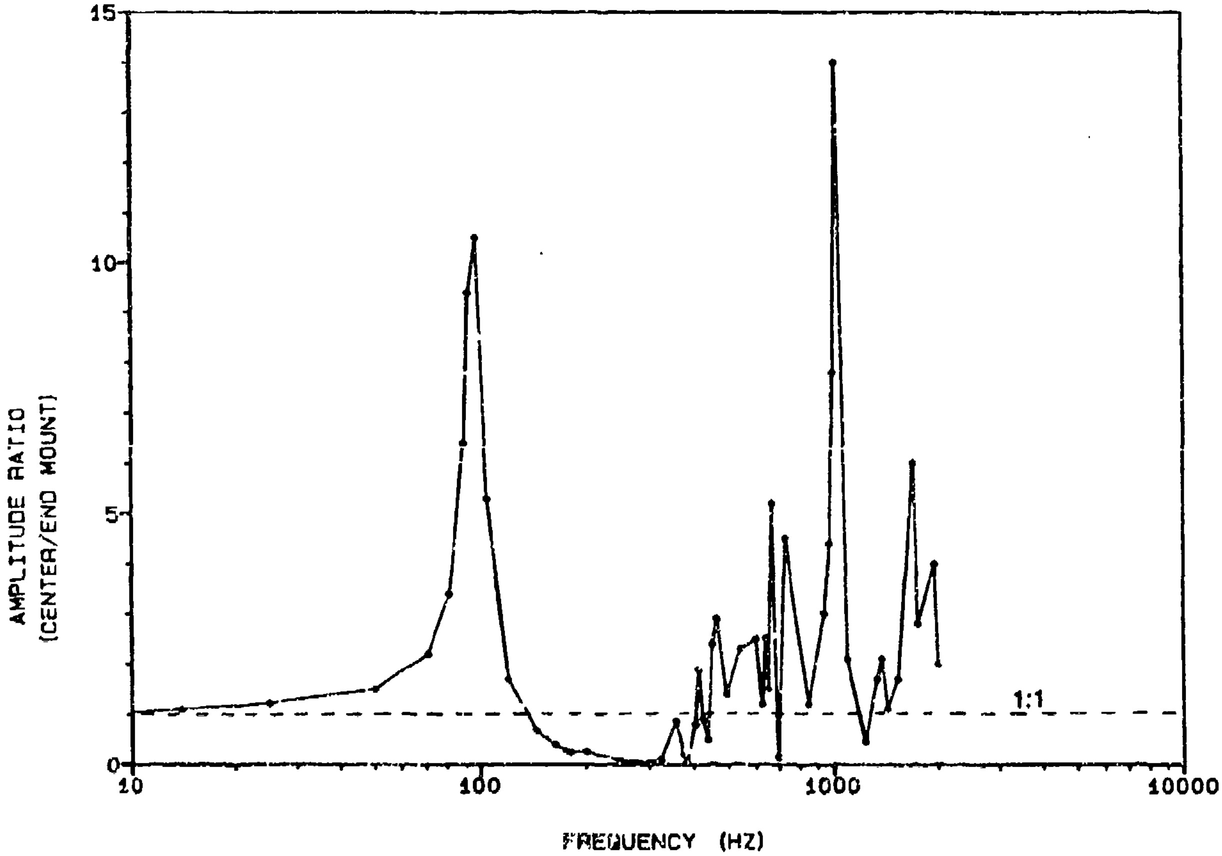


Figure 27. A/G ASM Vibration Response

4.7 Descent Transient

The speed of response of an ASM to changing operating conditions (inlet pressure, NEA flow, etc) is of interest for fighter applications where large amounts of NEA must be generated quickly during high speed descents. For this reason a test was devised which would evaluate the transient performance during a simulated high speed fighter type descent. This test was accomplished only with the A/G Technology ASM and was not performed with the Permea unit.

During this test, the inlet pressure, altitude (waste pressure) and NEA flow were varied over a 60 second period to simulate a hypothetical fighter descent from 45,000 Ft to sea level in one minute. Temperature was not a variable during these tests since it could not be changed by more than a few degrees over the 60 second period. The values of the three independent variables versus time are given in Figure 28 along with the resulting NEA percentO_2.

For each of the specific conditions measured during the transient test (specific inlet pressure, waste pressure and product flow), the steady state performance of the ASM was individually measured and plotted along with the transient data in Figure 28. Considering that the oxygen analyzer response is roughly three seconds and has not been compensated for in this transient data, the ASM performance during this type of descent can be assumed essentially steady state without significant error.

4.8 Destructive High Temperature Test

All of the testing previously described for both the A/G Technology and Permea ASMs was accomplished at temperatures thought to be conservative by the manufacturer. However, in order to be confident of the operating safety margin and to understand how an ASM will fail, it was desirable to perform a high temperature destructive test. This type of test was performed only with the Permea ASM and at the conclusion of all other Permea testing. A/G Technology would not agree to this type of destructive test.

For this test the Permea ASM was installed in the primary test set-up, inside the temperature controlled enclosure. The enclosure insulation and heater were modified so that elevated temperatures could be obtained.

The procedure for this high temperature test was to measure performance as temperature was increased above 200°F in small steps (approximately 20°F) until some obvious ASM failure or marked degradation occurred. In this sense the test was intentionally destructive

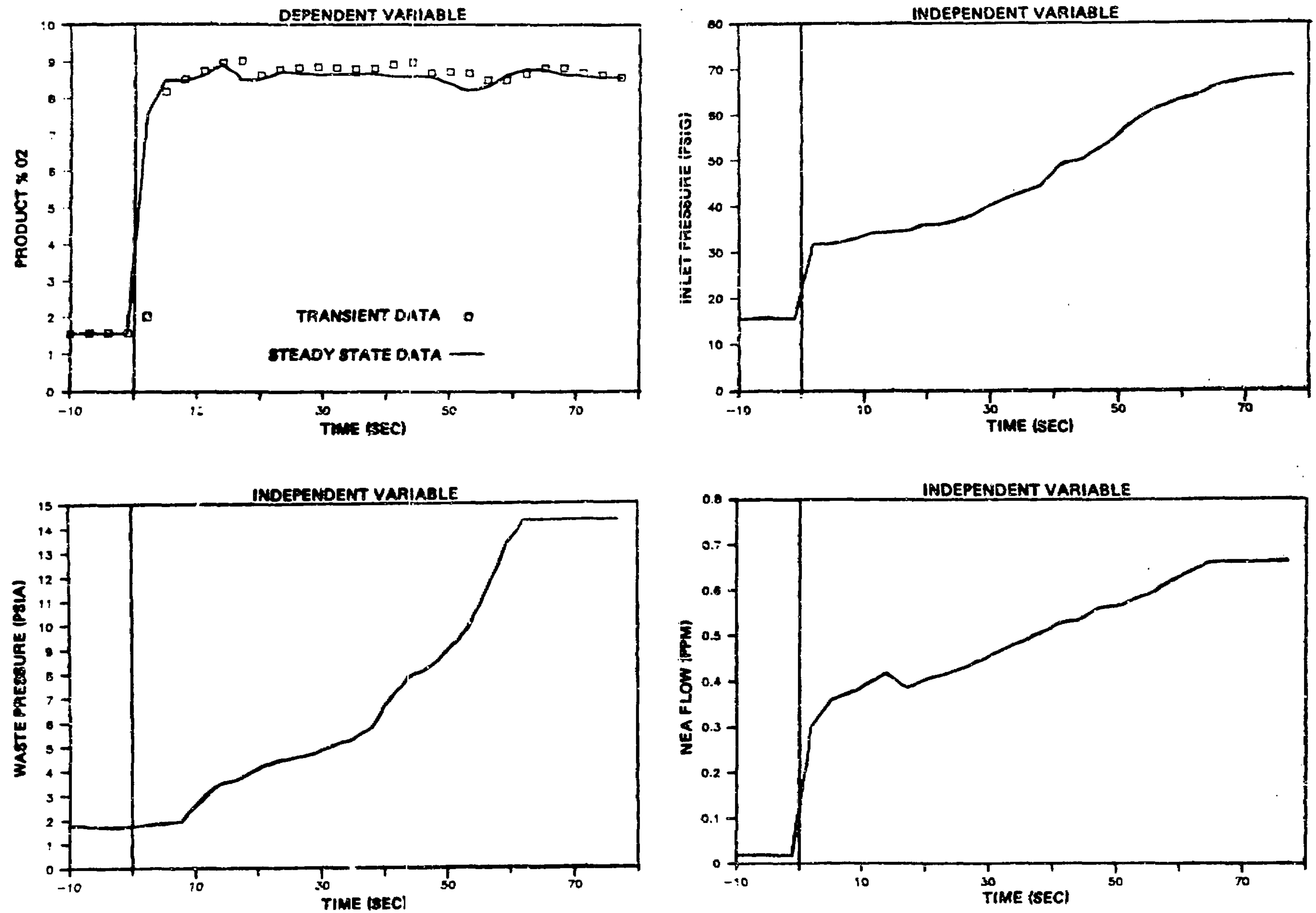


Figure 26. A/G Descent Transient

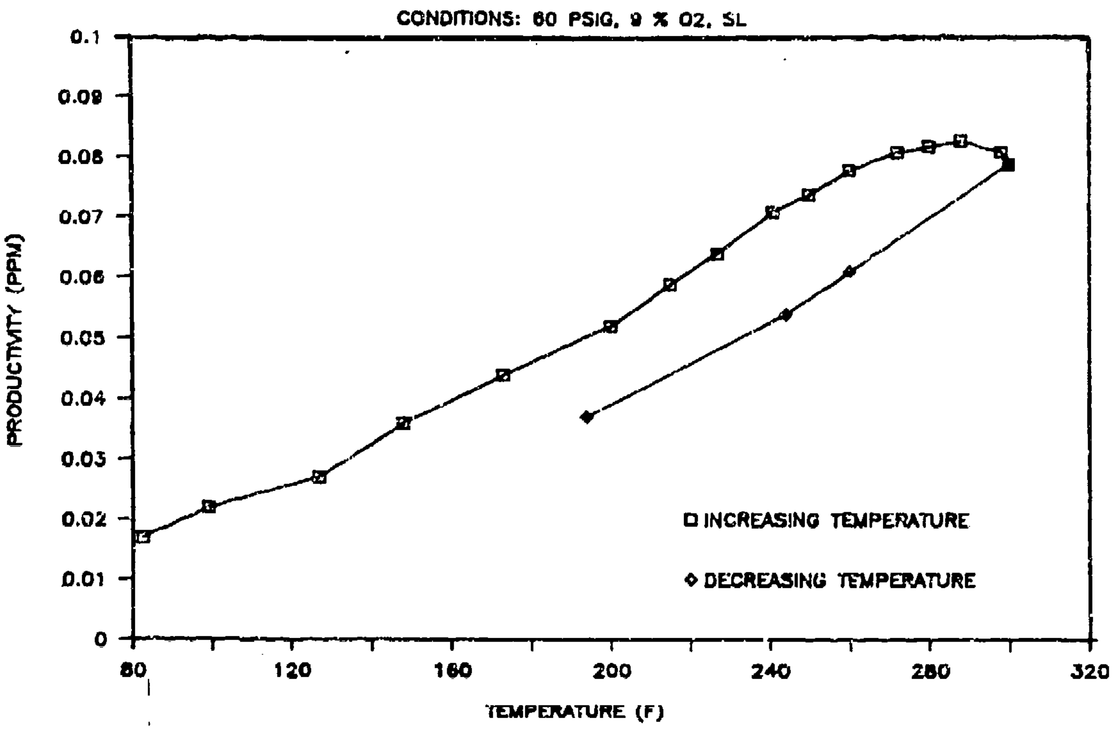
The test procedure consisted of the following:

- Start at ambient temperature.
- Operate at 60 PSIG inlet and 14.7 PSIA waste pressure throughout.
- Measure product flow and recovery vs. percentO_2 and obtain specific data at 9 %O_2.
- Repeat these measurements at 100°F, 150°F, 200°F and then 20°F intervals until results indicate a failure has occurred.

Performance was carefully analyzed at each temperature in order to detect when damage or a failure had occurred. These tests were accomplished over a three day period; long term high temperature stability data were not obtained due to test schedule priorities. In general, the ASM was operated at each temperature for an amount of time sufficient to obtain thermal equilibrium, roughly one hour. Since inlet flow increased with temperature, causing the thermal time constant to decrease (see discussion in Section 5.9), less time was required to obtain stable data at higher temperatures. An exception to this procedure was taken at the operating temperature of 250°F where the unit was maintained for an 8 hour period with no observed change in performance.

The results of this high temperature test are presented in Figure 29. As temperature was increased, it was expected that productivity would show a steady increase and recovery would show a steady decrease. When data indicated a deviation from this normal trend, some sort of damage to the ASM was assumed. No gross failures were observed and in fact no obvious change in performance was detected until the temperature exceeded the 280°F range at which point the productivity began to slowly drop. Up to 280°F, performance was considered to be normal. Note in Figure 29 that recovery data are not given below 200°F due to limitations of the inlet flow meter.

These results suggest that operation in the neighborhood of 250°F may be feasible for the Permea membrane. This could improve productivity by a nominal 50 percent (compared to 200°F operation) without significantly affecting the efficiency and also bring OBIGGS technology significantly closer to operating on airframe bleed air. However, these data must be viewed strictly as preliminary



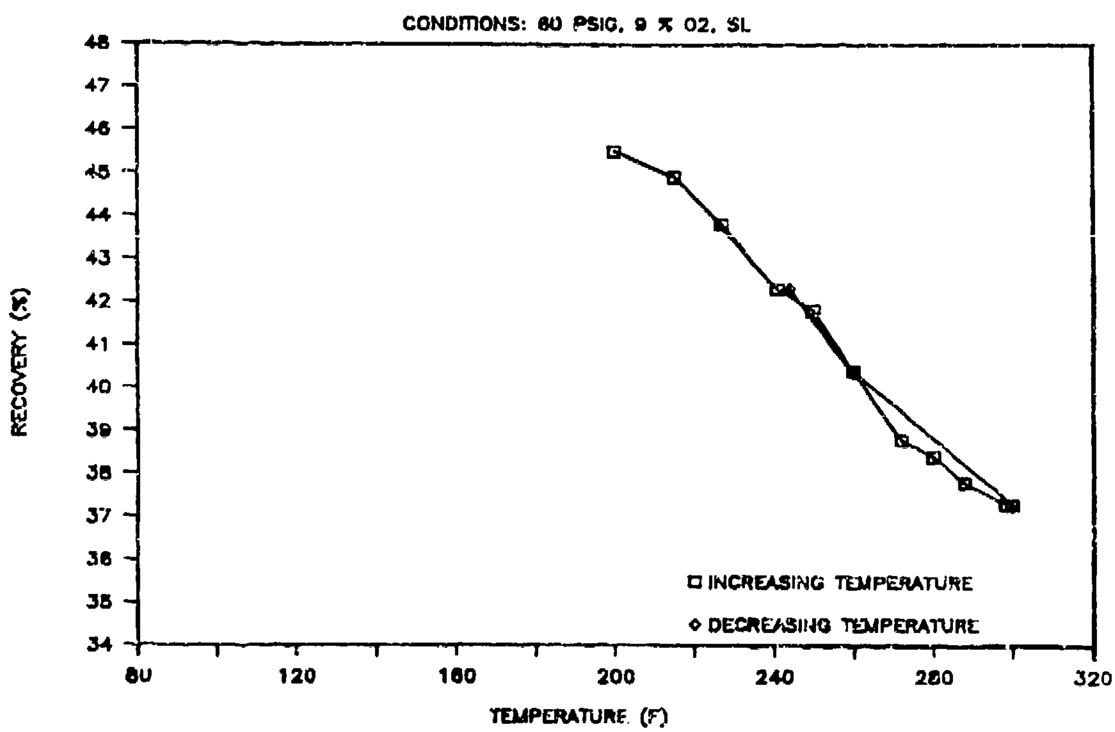


Figure 29. Permea High Temperature Test

until additional long term testing is performed at these elevated temperatures. Without further tests, the effect of higher operating temperatures (above 200°F) on degradation rate will not be known and may be unacceptable.

During this series of high temperature tests, a partial seal failure occurred on the inlet end of the Permea ASM (this seal prevents high pressure inlet air from leaking past the tube sheet). Seal leakage was noticed after completing the first series of tests above 200°F. During all subsequent attempts to operate the ASM, severe seal leakage occurred when the unit was first pressurized and persisted for varying amounts of time (no longer than about one minute) at which point the seal appeared to "seat". The ASM would then operate correctly until the pressure was again cycled. Had this seal continued to leak during the tests, measurements of ASM recovery would have detected anything of significance.

5.0 DATA ANALYSIS AND COMPARISONS

5.1 Mathematical Performance Models

The performance of all currently known ASMs can be characterized by the following general functions:

$$\text{percent}O_2 = f(V_{nea}, P_{asm,in}, P_{waste}, Temp)$$

$$Rec = f(\%O_2, P_{asm,in}\ P_{waste}, Temp)$$

These functions apply to the performance of both the A/G Technology and Permea ASMs. This performance can be summarized by noting that six variables (listed above) are needed to describe ASM performance. Any two of the six can be dependent while the other four are independent. To speed performance testing, percentO_2 and recovery were chosen as dependent variables and this has been followed in the mathematical modeling presented here.

By examining the data presented in Section 4.1 and Appendices D and E, the difficulty of completely describing the performance of the ASM in a simple graphical manner can be seen when two dependent and four independent variables are involved. For that reason, the mathematical performance models presented here have been found to be very useful. For example, using only discrete test data points, specific analyses frequently require that data be cross plotted and interpolated before the performance at a given operating point is obtained. This is a cumbersome task at best and often limits or precludes an analysis entirely. Use of the simple performance models presented here makes such an analysis considerably easier. These models are devised so that a single equation can be easily programmed in a line of a computer program or a single cell of spreadsheet on a personal computer.

Models are presented here for both of the A/G Technology ASMs (#1 and #2) and the Permea ASM. These models were developed largely on a trial and error basis using Lotus 123 on an IBM PC. While the details will not be discussed, the model development generally proceeded as follows:

- NEA flow and inlet pressure were first modeled. A single term was derived that allowed $\%O_2$ and recovery to be plotted as a single line at a constant waste pressure and temperature.

- Then a term describing the effects of waste pressure was added while temperature was still held constant.

- Finally a temperature term was added that allowed all data to be roughly plotted as a single line (not necessarily linear).

The values of constants were determined by trial and error using a computer graphics display for visual feedback. A nonlinear regression analysis was also used for this purpose but proved inferior to the visual method, especially when it was desirable to weight certain performance ranges.

Mathematical models were developed using this procedure for both A/G ASMs and the Permea ASM and are presented in Figures 30 through 32. Straight line approximations are offered which are reasonably good fits in the 5 to 9 percent O_2 range. Other ranges of can be fitted if desired. Explicit equations are given below for calculating percentO_2 and recovery in the 5 to 9 percent O_2 range.

$$\%O_2 = 207\left[\left(\frac{W^{.6}}{P^{.7}} + \frac{.4}{P}\right)\left(\frac{560}{T}\right)^{1.7}\right] - 17\left(\Delta P_r^{-1.4}\right) - 1.52$$

$$Rec = 4.68\left[\%O_2 - \frac{98}{P} + 18\left(\Delta P_r^{-1.4}\right) + 4\left(1 - \left(\frac{T}{560}\right)^4\right)\right] + 5.0$$

$\Big\}$ $A/G_{(ASM\ \#1)}$

$$\%O_2 = 595\left[\left(\frac{W^{.5}}{P^{.65}} + \frac{.15}{P}\right)\left(\frac{660}{T}\right)^{2.5}\right] - 25\left(\Delta P_r^{-1.4}\right) - 4.15$$

$$Rec = 4.34\left[\%O_2 - \frac{110}{P} + 25\left(\Delta P_r^{-1.4}\right) + 4\left(1 - \left(\frac{T}{660}\right)^4\right)\right] + 16.0$$

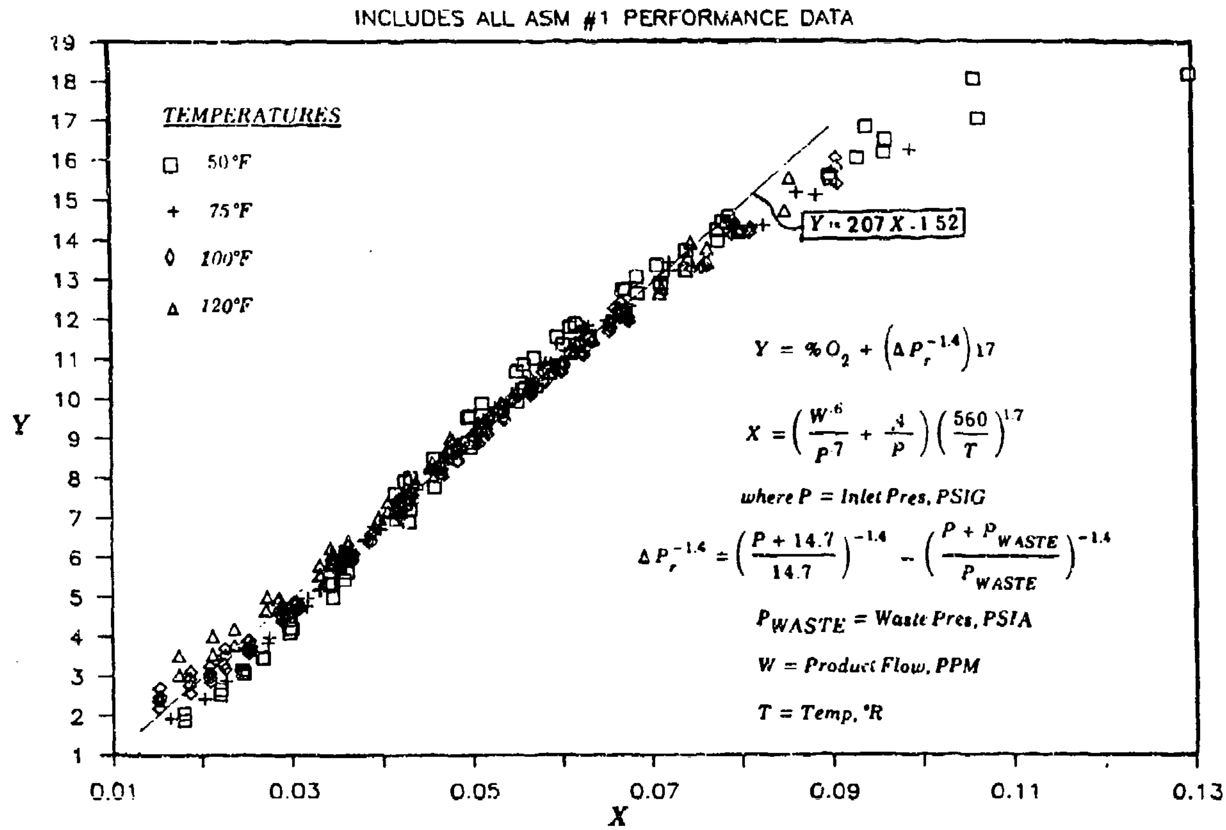
$\Big\}$ *Permea*

where: P = *ASM Inlet Pressure, PSIG*

$$\Delta P_r^{-1.4} = \left(\frac{P + 14.7}{14.7}\right)^{-1.4} - \left(\frac{P + P_{waste}}{P_{waste}}\right)^{-1.4}$$

P_{WASTE} = *ASM Waste Pressure, PSIA*

T = *ASM Temperature, °R*



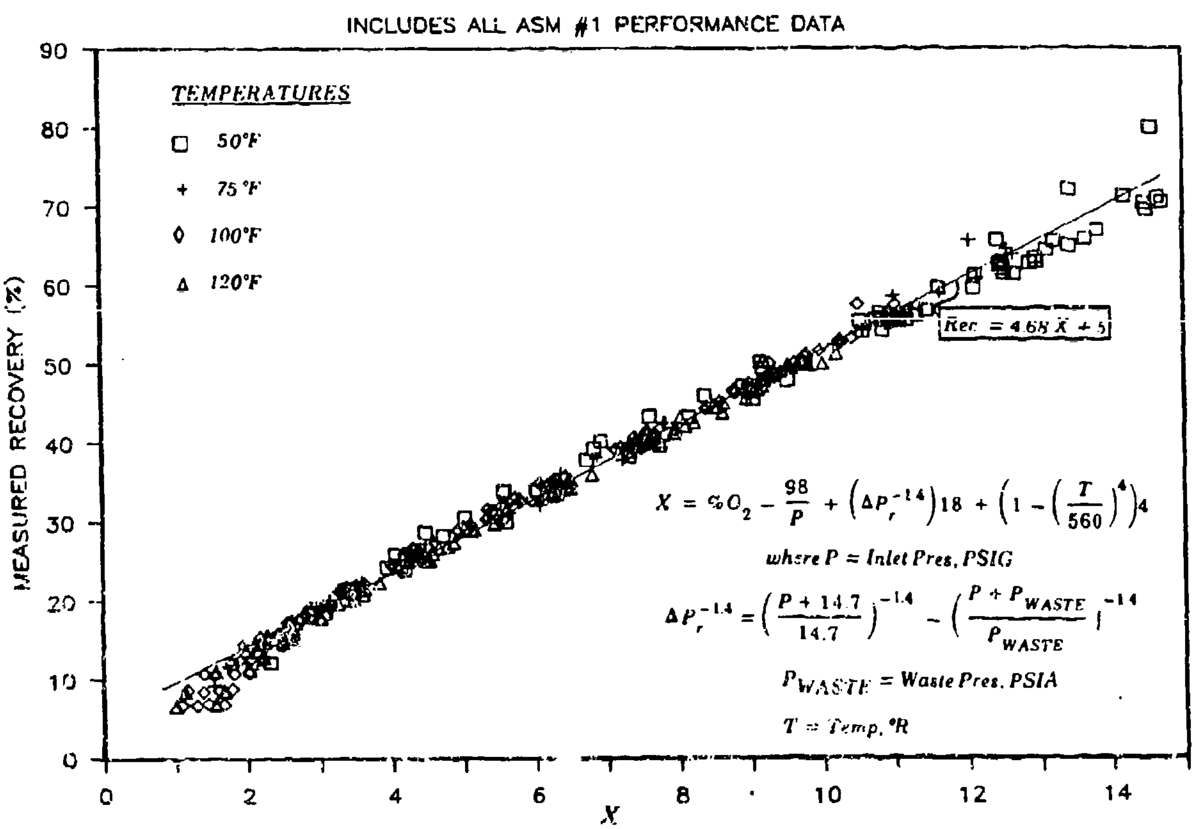
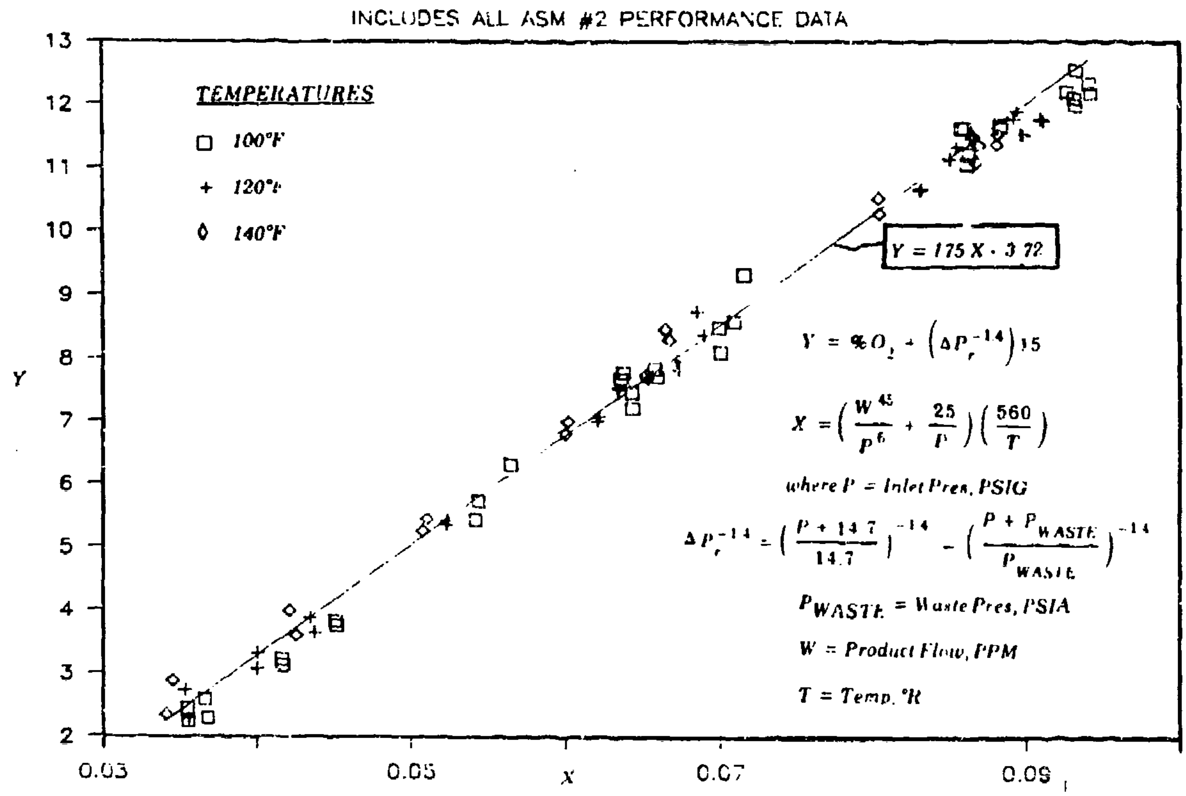


Figure 30. A/G ASM #1 Performance Model



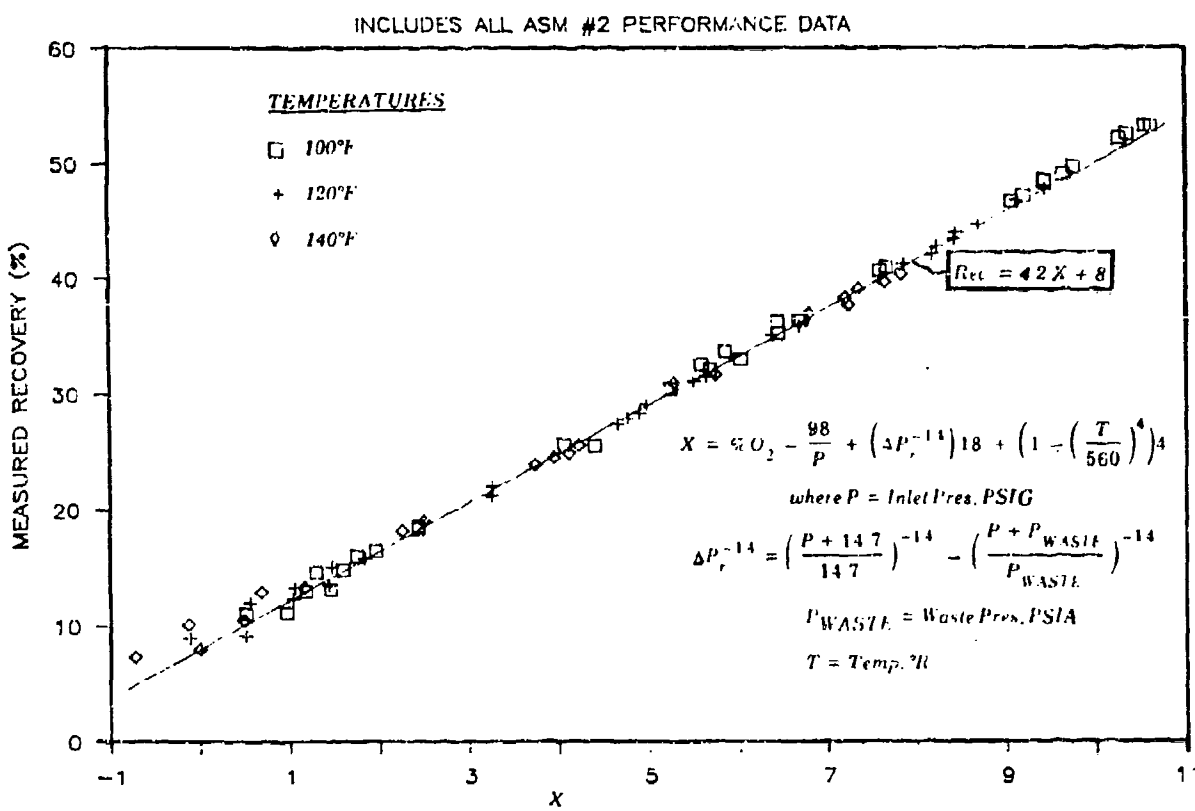


Figure 31. A/G ASM #2 Performance Model

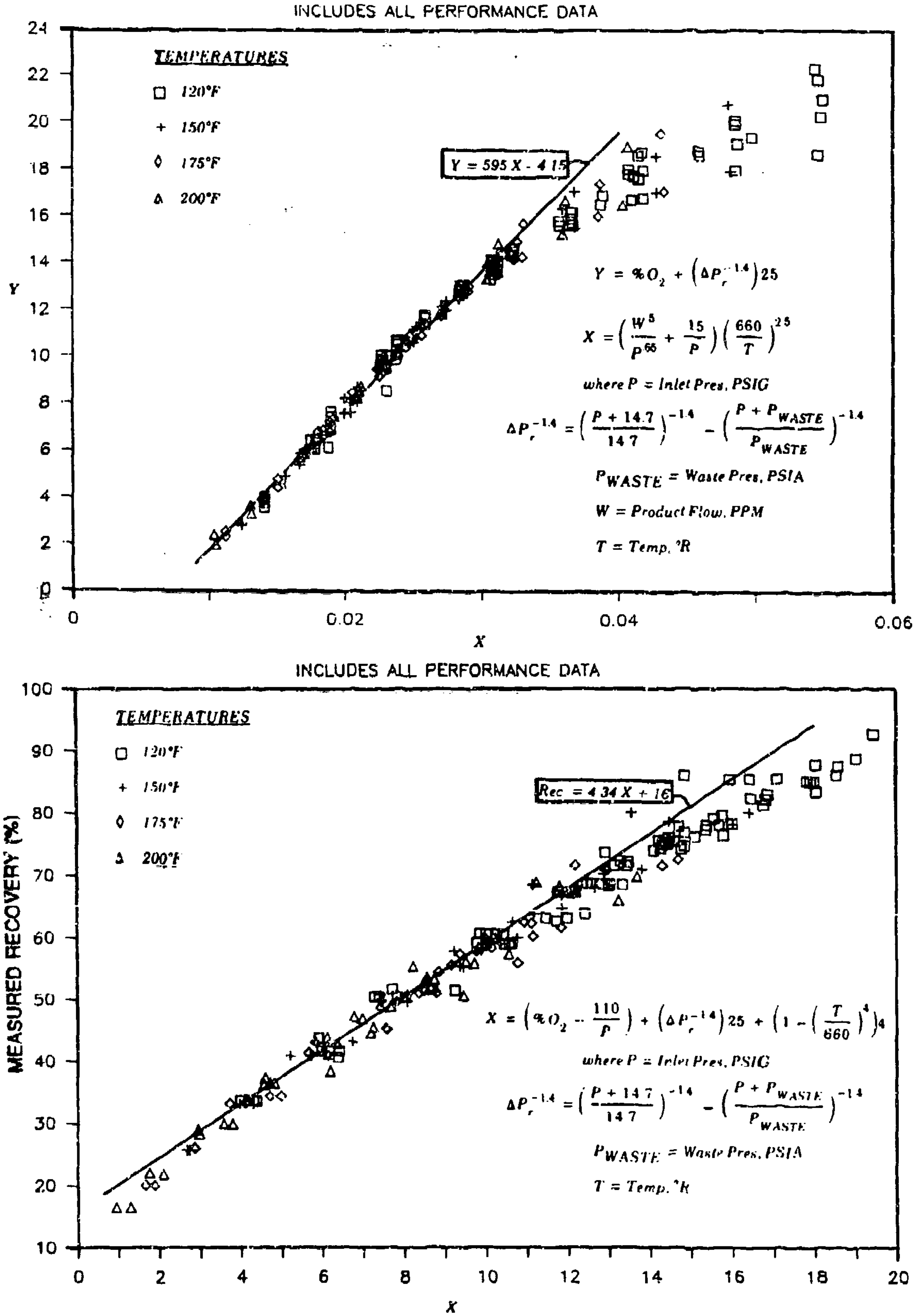


Figure 32 . Permea Performance Model

These models are specifically valid only for ASMs of the size tested here. However, they can be easily and accurately adapted to any size ASM that uses the same fibers by simply inserting a size factor in front of the NEA flow rate term wherever it appears. For example:

If,

$\%O_2 = f(W^{.6})$ for a specific ASM, then

$\%O_2 = f([S_r W]^{.6})$ for any size ASM (where S_r = Size Ratio).

The size ratio would ideally be the ratio of active fiber areas but could also be the ratio of fiber lengths or the square of fiber bundle diameters. The recovery models are independent of ASM size.

5.2 General ASM Comparison

The A/G and Permea ASMs, along with the Clifton molecular sieve ASM have been compared qualitatively in Table 15.

Table 15. General ASM Comparison

Category	A/G	Clifton	Permea
Operating pressure	Med	Low	Med-high
Operating temperature	Med	Low	High
ASM weight	Low	High	Med
Bleed penalty	Med	High	Low
Moving parts	None	Yes	None
Reliability	Unkwn	Proven	Unkwn
Size	Small	Med	Med
Thermal time constant	Small	Large	Med

It is obvious that the new advanced membrane ASMs appear to be superior in virtually every category. The reliability of a membrane unit is largely unknown and will not be firmly established until operational experience is obtained. While the ideal operating pressure for the membrane units is listed as being higher than that of the molecular sieve, the weight penalty analysis presented in the following sections will show that a membrane unit still offers significant weight savings, even at relatively low pressures.

5.3 ASM Weight Comparison

Weight is one of the most important considerations for the application of OBIGGS to airplane fuel tank inerting. Therefore, it is of interest to make direct weight comparisons at specific conditions between the various ASM technologies. The ASM weight required for a specific application can be scaled from prototype test data available in this report for the A/G and Permea advanced ASMs and from other sources for Clifton and DOW. The specific conditions chosen for this ASM weight comparison are as follows:

- 1 PPM NEA_5
- 36 inch Maximum Overall ASM Length
- 27,000 Ft Operating Altitude (5 PSIA Waste Pressure)
- Individualized ASM Operating Temperatures
  - 100°F for A/G
  - 200°F for Permea
  - 75°F for DOW
  - 40°F for Clifton

The operating temperatures chosen for the A/G and Permea units were based on nominal temperatures at or slightly below those at which most of the test data was obtained and endurance testing performed. The temperatures chosen for DOW and Clifton were considered optimum in earlier test programs (Reference 1).

One method of scaling test data is termed direct weight scale-up. Direct weight scale-up is accomplished by simply multiplying the weight of the tested ASM by the ratio of the desired to tested NEA flow. There are significant problems with this method since ASMs tested in this program as well as earlier programs were not airplane weight units. Further, direct scale-up is equivalent to utilizing multiple ASMs with the same diameter and length as the tested units and does not produce an efficient (from a weight standpoint) OBIGGS design.

The A/G and Permea ASMs tested in this program were not true airplane weight units and can be expected to be lightened considerably during design refinements for specific airplane applications. The A/G unit was the only possible exception since it was of reasonable size (2.5 inch OD fiber bundle) and its case was relatively light. Therefore, a method of estimating realistic ASM weights was developed for A/G and Permea ASMs of any diameter or length to aid in making more meaningful comparisons and to demonstrate future weight potentials. Due to the external fiber pressurization in the DOW ASM and the fundamental differences in the Clifton ASM, these two units were handled differently.

The DOW ASM (Reference 1) was a 9 inch OD by 46 inch long unit and therefore of a reasonably large airplane size. Except for the case, the weight of the DOW ASM would not be expected to change significantly during airplane design refinements. For the purposes of this weight comparison, an airplane weight case was estimated for the DOW unit and resulted in a total estimated weight of 195 Lbs for the system tested in Reference 1. The estimated DOW weights for this analysis were scaled directly from this 195 Lb estimate.

The Clifton ASM (Reference 1) presented special problems when estimating realistic airplane weights. The Clifton unit tested in Reference 1 was much heavier than an airplane unit would be and therefore its weight could not be used for direct scale-up. Actual weight estimates and performance figures for the latest Clifton MS unit being built for the C-17 were obtained from the Air Force Aeronautical Systems Division C-17 System Program Office. These estimates were used to revise downward the weight of the Clifton unit tested in Reference 1 from over 400 Lbs to an estimated airplane weight of 275 Lbs. The estimated Clifton weights for this analysis were then scaled directly from the 275 Lb estimate while still utilizing Reference 1 performance data.

The estimated weights of the A/G and Permea ASMs were calculated by estimating the individual weights of the three major components: fiber, tube sheet and case. The weight estimation procedure was as follows:

$$\text{ASM Wt} = Wt_{fiber} + Wt_{tube\ sheet} + Wt_{case}$$

where: Wt_{fiber} = weight of the active fiber

$Wt_{tube\ sheet}$ = weight of both tube sheets

Wt_{case} = weight of outer case including end fittings

The weight of the active fibers was directly and accurately scaled as follows:

$$Wt_{fiber} = \text{Tested } Wt_{fiber} \times W_r$$

$$\text{where: } W_r = \frac{\text{Desired NEA Flow}}{\text{Tested NEA Flow}}$$

The tube sheet weight as a function of diameter has been estimated based on information from Permea and A/G Technology and is approximated by the following empirical relationship:

$$Wt_{tube\ sheet} = 0.053\ D^{2.5}$$

where: D = Tube sheet or ASM diameter (In)

Wt = Weight of both ends (Lbs)

The 2.5 power accounts for tube sheet area and also thickness growth with diameter. The tube sheet diameter is determined by the required fiber volume and length limitations. For the purposes of this comparison an airplane compartment was assumed to limit the ASM overall length to 36 inches. Three inches were allowed at each end of the ASM tube sheet and end fittings, leaving an active fiber length of 30 inches.

The volume of active fiber was computed similar to the fiber weight as follows:

$$Vol_{fiber} = \text{Tested } Vol_{fiber} \times W_r$$

The required fiber bundle diameter was then calculated as follows:

$$D = 2\sqrt{\frac{Vol_{fiber}}{L_{active}\pi}}$$

The weight of the ASM case was calculated at several diameters based on aluminum designed for 100 PSI operating pressure (safety factor = 1.5). The weight includes end fittings but no allowance was made for filters, hold down brackets, etc. The total projected case weight from these calculations as a function of diameter was approximated by the following empirical relationship:

$$Wt_{case} = 0.24\ D^{1.55} + 0.158\ D \text{ (for } L_{active} = 30 \text{ inch)}$$

where: D = Diameter (In)

Using the described weight estimation procedures, a weight comparison for the A/G, Clifton, DOW and Permea ASMs was performed (Figure 33). A breakdown of the weight estimates is given in Table 16. The ASM weights were chosen to be shown as a function of inlet pressure since pressure significantly affects ASM size.

Note that the A/G unit offers the greatest potential weight savings. When examining the data presented in Figure 33, note that a logarithmic scale was used due to the wide range of estimated weights for the four ASMs.

The largest diameter fiber bundle considered practical, by membrane manufacturers in general, is roughly 8 inches. If the required diameter exceeded this, multiple ASMs would probably be required. This factor was not addressed in this weight comparison and ASMs up to 16 inch diameter were assumed. For comparison purposes, the weight differences between one 16 inch unit and 4 each 8 inch units did not significantly alter the results. The weight penalty incurred by bundling smaller diameter ASMs is shown in Figure 34. Notice that bundling is advantageous for ASM diameters larger than 4 inches. However, this analysis does not consider the weight of manifolds which means the actual penalties will be somewhat larger.

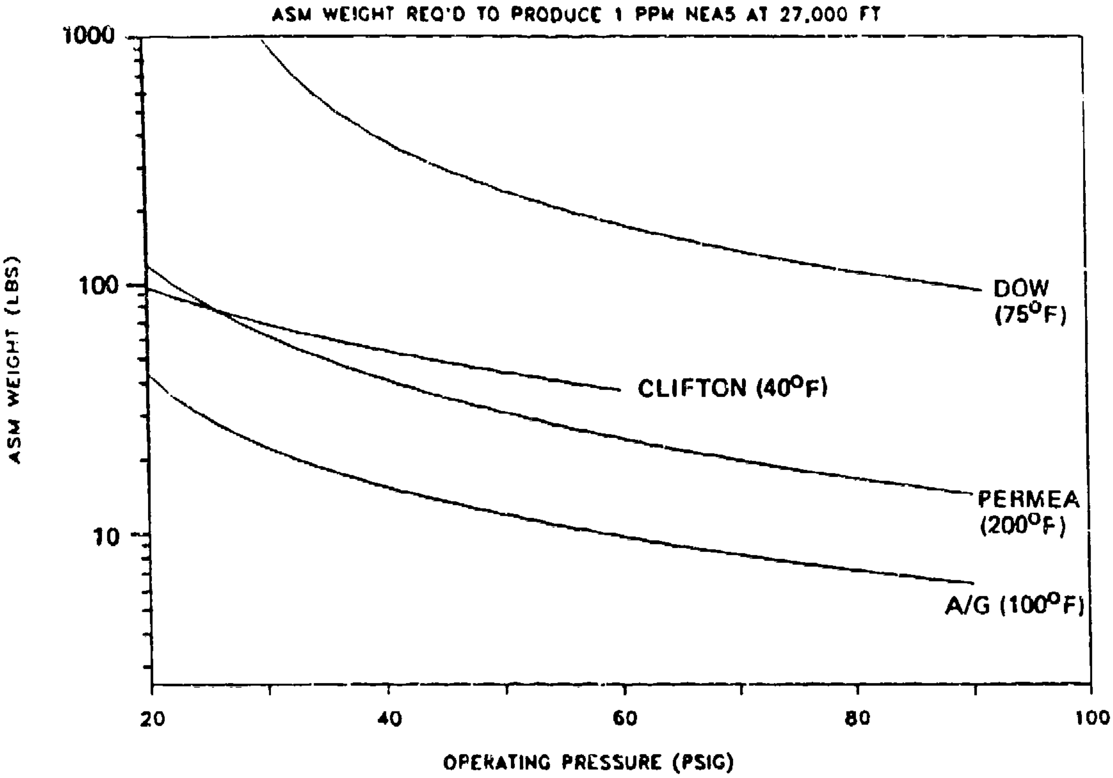


Figure 33. Comparison of Estimated ASM Weights

Table 16. ASM Weight Comparison Summary

ASM	Inlet pres. (PSIG)	Tested NEA flow (ppm)	W_r	Estimated airplane weight: Req'd fiber wt (lbs)	Req'd fiber vol (in³)	Req'd bundle dia (in)	Tube sht wt (lbs)	Case wt (lbs)	Total ASM wt (lbs)
A/G	20	0 083	12.1	16 0	2431	10 2	17.4	10.3	43.7
	30	0 161	6 2	8 2	1245	7 3	7 5	6 3	22.1
	40	0 232	4.3	5 7	865	6.1	4 8	4 9	15.3
	55	0.336	3.0	3 9	598	5.0	3 0	3.7	10.7
	70	0 441	2.3	3.0	456	4 4	2.2	3.1	8.2
	90	0 582	1.7	2 3	346	3 8	1.5	2.5	6.3
Permea	20	0 011	94 1	37 7	6589	16.7	60.6	21.5	119.8
	30	0 019	51 4	20 5	3595	12.4	28 4	13 8	62.7
	40	0 029	34 5	13.8	2414	10 1	17.3	10 3	41 3
	55	0 044	22.6	9 1	1584	8.2	10 2	7 6	26.8
	70	0 060	16 6	6 6	1163	7.0	6.9	6 0	19 6
	90	0 082	12 1	4 8	849	6.0	4 7	4 8	14 3
DOW	30	0 199	5 02	Not estimated					978.4
	40	0 506	1 98						385 4
	55	0 966	1 03						201 9
	70	1 426	0 70						136 7
	90	2.040	0 49						95 6
Clifton	20	2 827	0 35	Not applicable					97 3
	30	3 957	0 25						69 5
	40	5 087	0.20						54 1
	60	7 347	0 14						37 4

Conditions: 1 ppm NEA, 36" overall ASM length, 27,000 ft. altitude. A/G @ 100°F, Permea @ 200°F, DOW @ 75°F, Clifton @ 40°F

$W_r = \frac{\text{desired NEA flow}}{\text{tested NEA flow}}$

Before these weight estimates can be realized, actual manufacturing capability must permit larger diameter ASMs than those tested in addition to lighter weight cases. The weight of future ASMs produced by specific manufacturers may differ from estimates presented here. It is interesting to note however that a direct scale up of the A/G unit tested in this program yields weights that are still less than the estimated airplane weights for Permea.

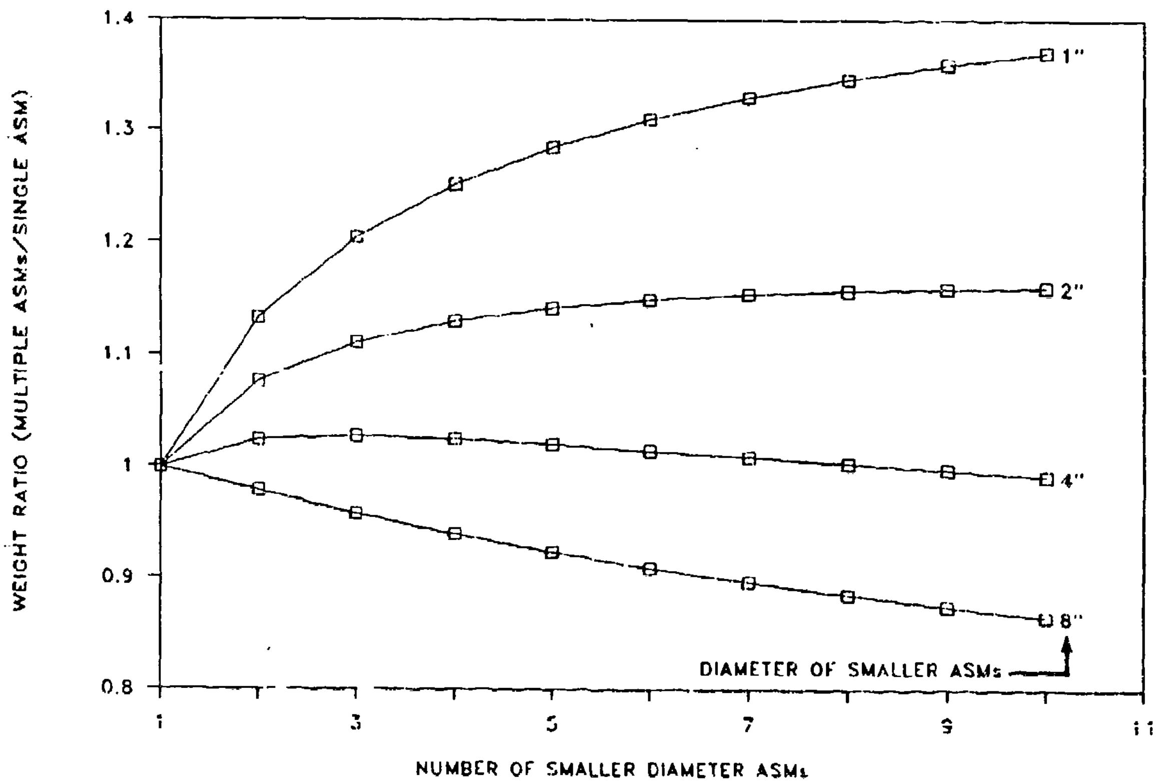


Figure 34. Weight Penalty Incurred Using Multiple Smaller Diameter ASMs

Examination of Table 16 reveals that the A/G unit enjoys the distinct and fundamental advantage of requiring less than half the weight and volume of fibers compared to Permea. Given equal fiber bundle packaging technology, the A/G unit should have an inherent ASM weight and volume advantage.

As stated earlier, this entire weight analysis is based on the A/G and Permea ASMs operating at 100°F and 200°F, respectively. Higher temperature operation will alter the results of this analysis and this subject is specifically addressed in Section 5.5.

5.4 Total Airplane Weight Penalties

The weight of the ASM alone does not constitute the entire penalty for an OBIGGS application. The bleed air extracted, the weight of plumbing and the weight of equipment needed to cool the bleed air must also be considered.

The bleed air flow and associated cooling load required for the size ASM used in the previous weight analysis (1 PPM NEA_5 at 27,000 Ft) have been calculated and are presented in Figure 35. Since the DOW membrane unit is no longer being seriously considered for OBIGGS, it has been dropped from further analysis. Note that the Permea ASM, with its higher recovery and higher operating temperature, requires the least bleed flow and associated cooling. The Clifton molecular sieve requires the highest bleed flow and cooling due to a low operating temperature and poor recovery. The A/G unit is positioned between these two. Notice that unlike ASM weight, bleed flow and cooling load are not significantly affected by operating pressure. The cooling loads are based on a nominal bleed air temperature of 1000°F at the engine prior to entering the pre-cooler.

Before the bleed flows and cooling loads can be evaluated in terms of airplane weight penalties, the equipment weights required to produce them must be estimated. In order to estimate heat exchanger weights, etc., bleed air delivery and cooling systems of several different sizes were designed and empirical models developed to approximate their weights. A description of these bleed air systems are included in Appendix H. Two different types of airplanes were used for this analysis, an ATF-like airplane (sustained supersonic fighter) and a subsonic transport. It was felt that this approach would "bracket" the problem; the supersonic fighter representing the highest bleed cooling penalties and the transport representing the lowest. This assumption was based on the inherent difficulties encountered rejecting heat in a supersonic airplane with high stagnation air temperatures.

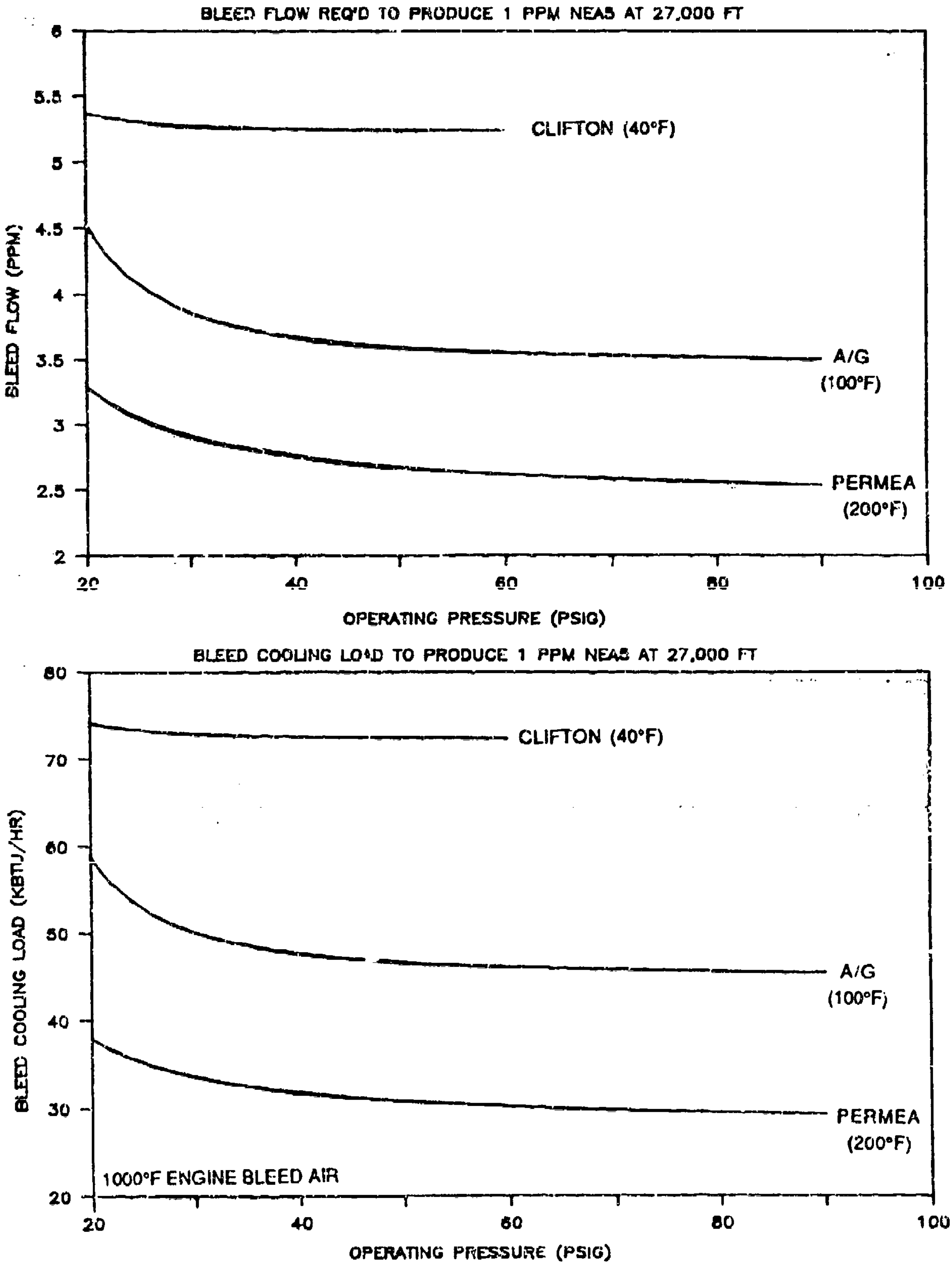


Figure 35. Comparison of Bleed Flow and Cooling Penalties

Using the empirical bleed system weight models (Appendix H), the bleed system weight penalties for the various ASMs were calculated and are presented in Figure 36 and Table 17. As would be expected, the Permea unit, with its high recovery and high operating temperature realizes the lowest bleed system weight penalties.

Table 17. Combined ASM and Bleed System Weight Penaltities

(All weights in lbs)

(a.) Generic ATF

ASM	Inlet pres (psig)	Est'd ASM wt	Pre-cooler growth	Pri HX growth	Sec HX	ECS growth	Supply duct	Total bleed wt penalty	ASM + bleed penalty
A/G	20	43.7	2.7	2.1	6.2	8.2	7.4	26.6	70.3
	40	15.3	2.2	1.7	5.4	7.0	6.2	22.5	37.8
	90	6.3	2.1	1.6	5.3	6.7	5.9	21.6	27.9
Permea	20	119.8	2.0	1.4	N/A	N/A	5.6	9.0	128.8
	40	41.3	1.7	1.2	N/A	N/A	4.9	7.7	49.1
	90	14.3	1.5	1.1	N/A	N/A	4.5	7.2	21.5
Clifton	20	97.3	3.2	2.4	10.5	14.1	8.5	38.8	136.0
	30	69.5	3.2	2.4	10.3	13.9	8.4	38.2	107.7
	60	37.4	3.1	2.4	10.3	13.9	8.3	38.0	75.4

(b.) Transport

ASM	Inlet pres (psig)	Est'd ASM wt	Pre-cooler growth	RAM HX	Supply duct	Total bleed wt penalty	ASM + bleed penalty
A/G	20	43.7	0.8	7.3	8.0	16.1	59.8
	40	15.3	0.7	6.0	7.2	13.8	29.2
	90	6.3	0.6	5.7	7.0	13.3	19.6
Permea	20	119.8	0.6	4.8	6.8	12.2	132.0
	40	41.3	0.5	4.0	6.2	10.7	52.1
	90	14.3	0.4	3.7	6.0	10.1	24.4
Clifton	20	97.3	1.0	9.2	8.7	18.9	116.2
	30	69.5	0.9	9.1	8.6	18.5	88.1
	60	37.4	0.9	9.0	8.6	18.5	56.0

Conditions: 1 ppm NEA, 30" overall ASM length, 27,000 ft. altitude, 1000°F bleed air, A/G @ 100°F, Permea @ 200°F, Clifton @ 40°F.

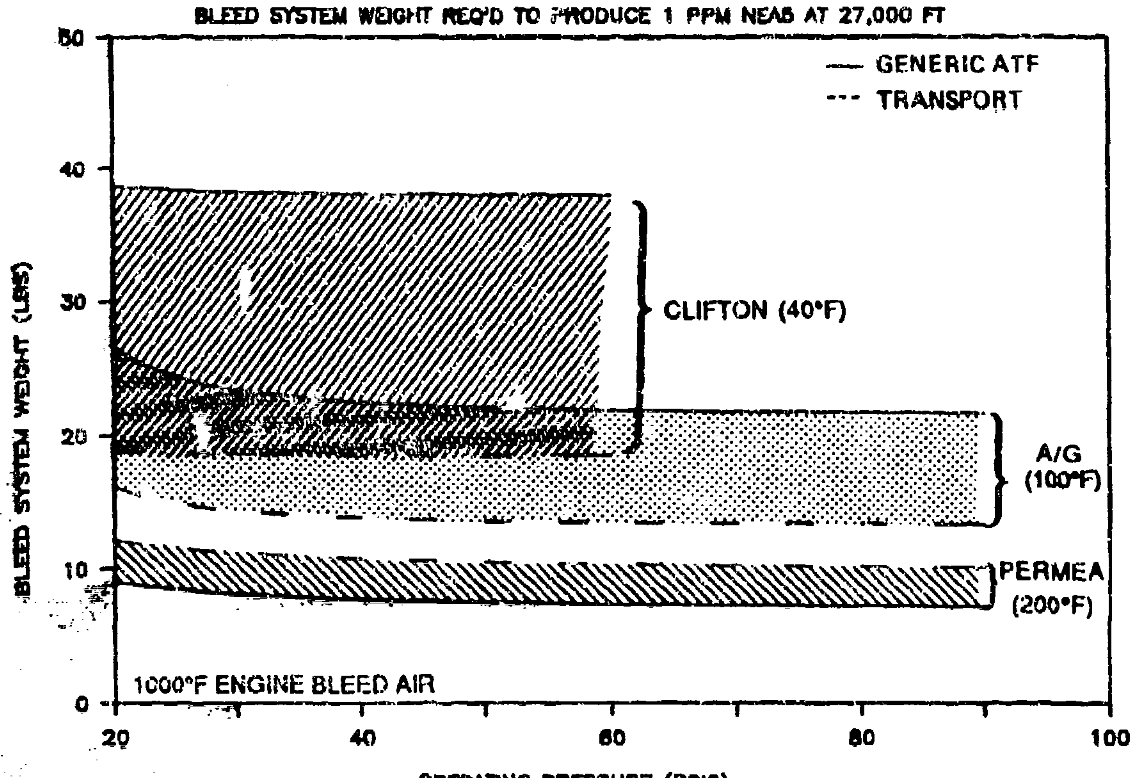


Figure 36 Comparison of Bleed System Weight Penalties

Note that with the Permea ASM, the ATF-like airplane bleed weight penalty is actually lower than that of the transport. This result runs counter to the initial assumption that it would be inherently more difficult to reject heat in an ATF-like airplane. Closer examination of data in Table 17 and Appendix H reveals that the use of a fuel/air heat exchanger without the need for a secondary heat exchanger with its ECS penalty in the ATF-like airplane is significantly lighter than the ram air heat exchanger in the transport, even at high altitude with relatively cold ram air (-60°F). Since the Permea ASM operates at 200°F, the 450°F bleed air can be cooled solely with fuel (roughly 140°F maximum fuel temperature) while the A/G unit requires a secondary heat exchanger to further reduce bleed temperature to 100°F.

Combining ASM weights (Figure 33) and bleed system weights (Figure 36), the total airplane weight penalty for the three ASMs is presented in Figure 37 and Table 17. Note that in certain pressure ranges the Permea ASM at 200°F appears to represent the lowest overall penalty even though the ASM itself is heavier than the A/G ASM at 100°F.

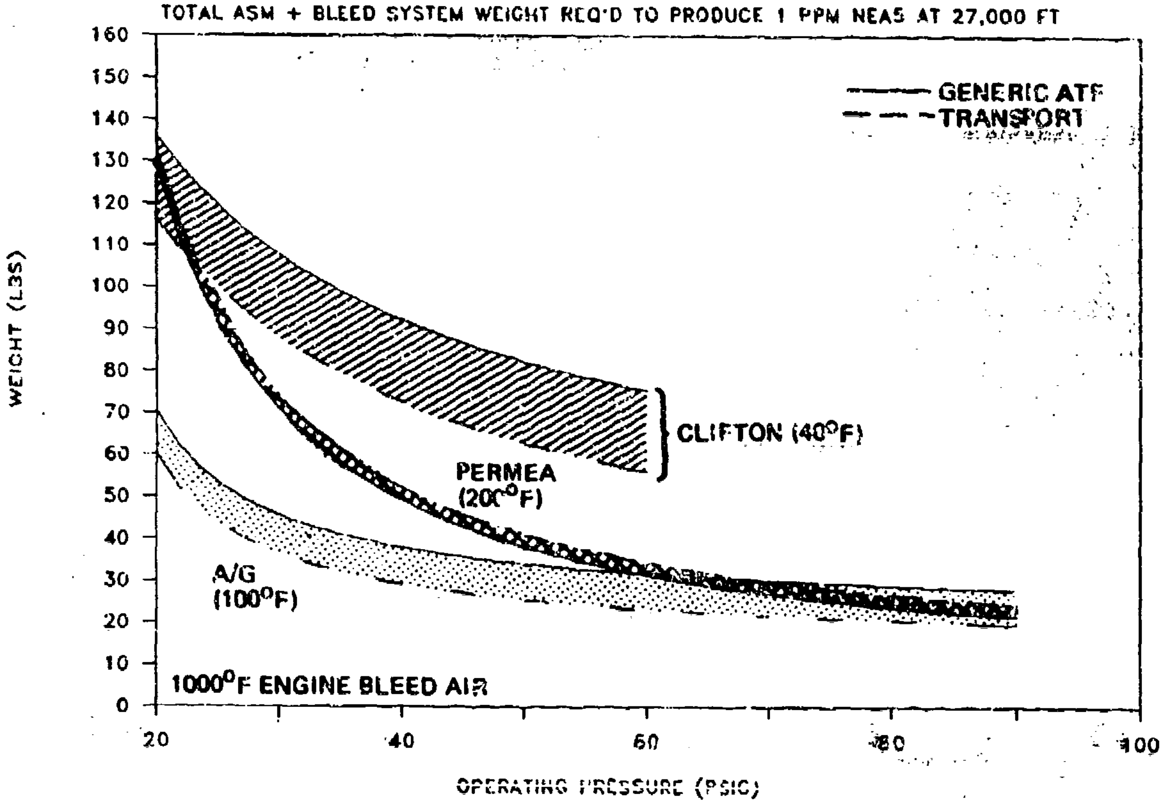


Figure 37. Comparison of Total Airplane Weight Penalties

This entire weight analysis (ASM and bleed system weight) was performed at the specific conditions of 1 PPM NEA flow at 5 percent O_2. While the magnitude of the weight penalties will change with desired NEA oxygen concentration, the relative ranking for total airplane weight was not found to be significantly sensitive to NEA concentration. In addition, the relative ranking was also not sensitive to NEA flow even though the ASM and bleed system component weights do not scale linearly with flow.

Note that, depending on the type of OBIGGS and the specific airplane application, other weight penalties can be associated with an OBIGGS, i.e. the NEA distribution system plumbing, fuel tank pressure regulators and fuel scrub nozzles would be additional components of a demand OBIGGS. Furthermore, the high pressure compressor and storage bottles would be major weight contributors to the total weight of the stored gas OBIGGS. The total weight penalties are not addressed in this report but total system weights are discussed in Reference 9.

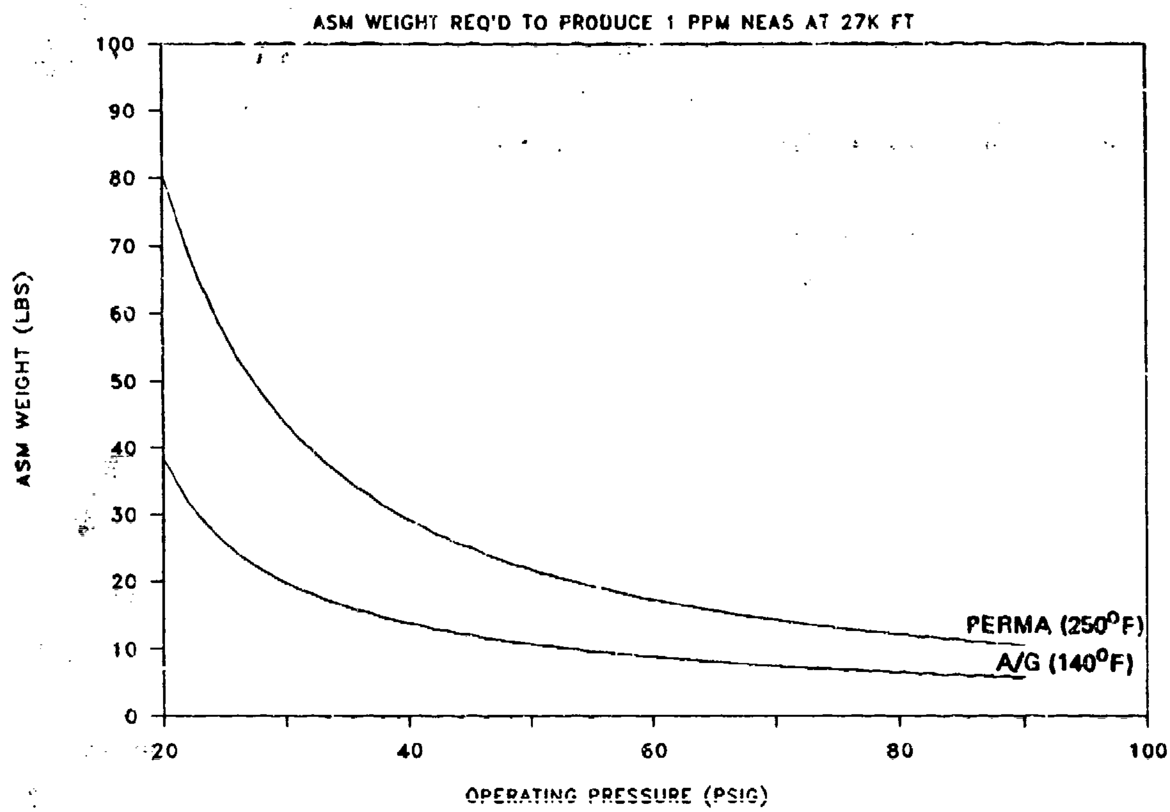
This weight analysis assumes that the size of bleed system components will be adjusted for varying ASM flow and delivery temperature requirements during the design process. If this is not the case, these bleed weight penalties will not be realized. For example, if an engine precooler is initially designed to accommodate growth in bleed air usage and therefore is not resized when OBIGGS is added to an airplane design, the weight penalty allotted to precooler growth in the analysis can not be "charged" to OBIGGS. This applies to other components as well.

5.5 Benefits of Higher ASM Operating Temperatures

The benefits of increasing ASM operating temperatures beyond those chosen for analysis in Sections 5.3 and 5.4 are of interest for future applications. The high temperature destructive test performed with the Permea ASM suggested that operation at temperatures as high as 250°F may be possible for the Permea ASM (although not yet proven for long durations). Increasing Permea's operating temperature from 200°F to 250°F raised productivity by more than 40 percent. While the upper temperature limit of the A/G unit was not explored, it may also be capable of operating at higher temperatures.

The analysis presented in Sections 5.3 and 5.4 was redone for A/G and Permea at 140°F and 250°F, respectively (Figure 38). These temperatures were the highest successfully tested for each unit, although the ASMs were held at these elevated temperatures for only short durations (8 hours or less). While the Permea ASM weight is reduced significantly by increasing its operating temperature by 50°F, the overall airplane weight penalty (ASM + bleed penalty) and the relative ranking between A/G and Permea are not significantly affected.

In order to better understand the effect of operating temperature, these analytical procedures were used to assess weight penalties as a function of temperature. The conditions and procedures utilized in Sections 5.3 and 5.4 were again used to examine the temperature effects on weight penalties except that operating pressure was fixed at a nominal 50 PSIG while temperature was varied over a relatively wide range (Figure 39 and Table 18). The A/G performance above 140°F is extrapolated and Permea performance above 200°F is



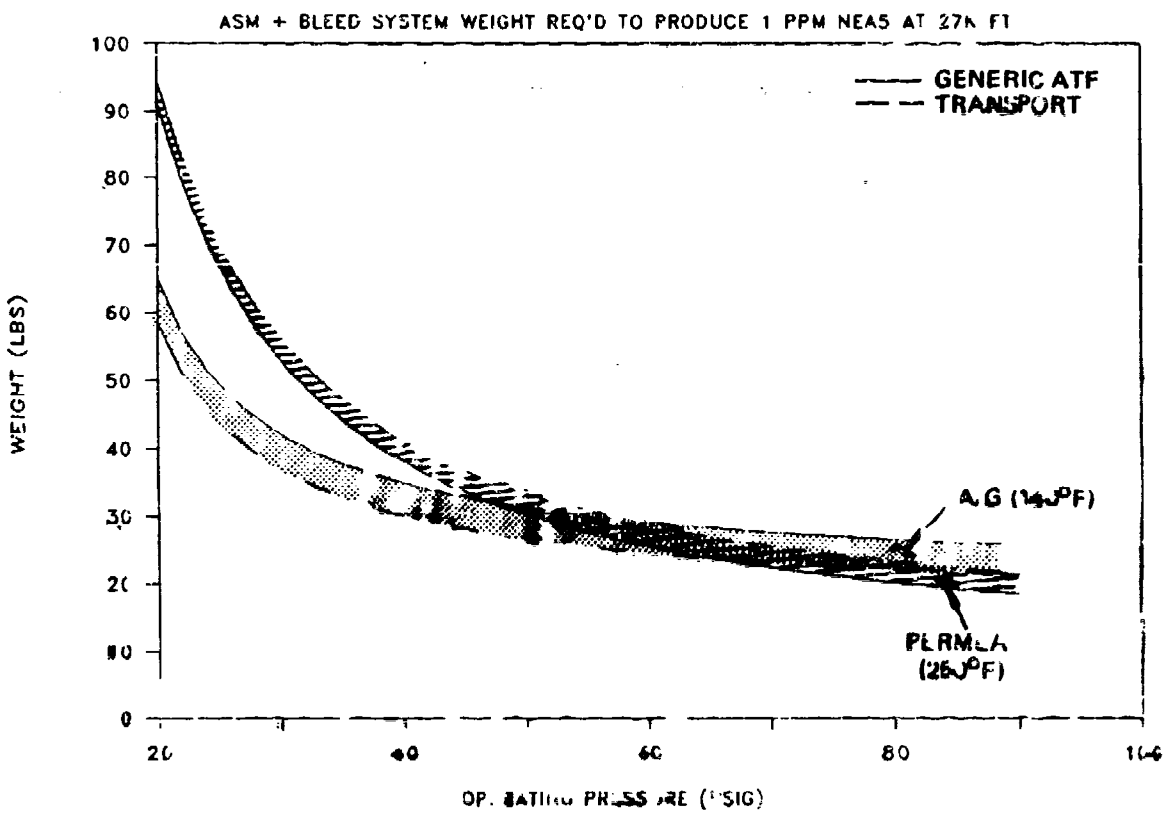


Figure 38. Comparison of Weight Results at Higher Temperatures

based on limited data obtained during the high temperature destructive test (Section 4.8). There is no assurance that either unit will operate successfully at these elevated temperatures. Note that in most cases, the bleed penalty actually increases with ASM operating temperature due to the overriding associated increase in bleed flow.

Table 18. Benefits of Higher ASM Operating Temperatures

(All weights in lbs)

(a.) Generic ATF

ASM	ASM temp (°F)	Est'd ASM wt	Bleed flow (PPM)	Cooling load (kbtu/hr)	Pre-cooler growth	Pri HX growth	Sec HX	ECS growth	Supply duct	Total bleed wt penalty	ASM + bleed penalty
A/G	80	12.5	3.3	44	2.0	1.5	6.0	7.5	5.6	22.6	35.2
	100	11.9	3.6	47	2.2	1.6	5.4	6.8	6.1	22.1	34.0
	140	10.7	4.6	57	2.8	2.1	3.6	4.7	7.5	20.6	31.3
	160	10.2	5.5	66	3.3	2.5	1.9	2.6	8.7	19.0	29.2
	170	10.0	6.1	73	3.6	2.7	0.0	0.0	9.5	15.9	25.8
Permea	175	36.5	2.5	30	1.5	1.1	NA	NA	4.5	7.2	43.6
	200	30.4	[illegible].7	31	1.6	1.1	NA	NA	4.7	7.5	37.9
	225	25.6	[illegible].9	32	1.7	1.1	NA	NA	5.0	7.9	33.6
	250	21.8	3.2	34	1.9	1.2	NA	NA	5.4	8.5	30.3
	275	18.7	3.5	37	2.1	1.2	NA	NA	6.0	9.3	28.0

(b.) Transport

ASM	ASM temp (°F)	Est'd ASM wt	Bleed flow (PPM)	Cooling load (kbtu/hr)	Pre-cooler growth	RAM HX	Supply duct	Total bleed wt penalty	ASM + bleed penalty
A/G	80	12.5	3.3	44	0.6	5.4	6.8	12.9	25.4
	100	11.9	3.6	47	0.6	5.8	7.1	13.6	25.5
	140	10.[illegible]	4.[illegible]	57	0.8	7.1	8.1	16.0	26.7
	160	10.[illegible]	5.5	66	1.0	8.3	8.8	18.1	28.3
	170	1[illegible]	6.1	73	1.1	9.1	9.3	19.5	29.5
Permea	175	36.5	2.5	30	0.4	3.7	6.0	10.2	46.6
	200	30.4	2.7	3[illegible]	0.5	3.9	6.2	10.5	40.9
	225	25.6	2.9	3[illegible]	0.5	4.1	6.4	10.9	36.6
	250	21.8	3.2	34	0.6	4.3	6.7	11.5	33.3
	275	18.7	3.5	37	0.6	4.7	7.1	12.4	31.0

Conditions. 1 PPM NEA_5, 50 PSIG Inlet Pressure, 36" Overall ASM Length, 27,000 Ft Altitude, 1000°F Bleed Air.

Note in Table 18 that even though the ASM operating temperature is increasing (bleed air delta T decreases), the actual cooling load increases due to the overriding increase in bleed flow. Note also that the cooling load does not always directly effect bleed weight penalties; for the ATF-like airplane comparison, the bleed penalty for A/G actually goes down while cooling load increases due to the gradual elimination of the secondary heat exchanger and ECS growth penalties. The need to cool bleed air below 170°F entailed the most significant weight penalties on the ATF-like airplane. All other comparisons show bleed weight penalties increasing with temperature. The overall weight penalty for the Permea unit decreases with temperature due to the overriding drop in ASM weight. However, the overall penalty for A/G decreases for the ATF-like airplane and increases for the transport.

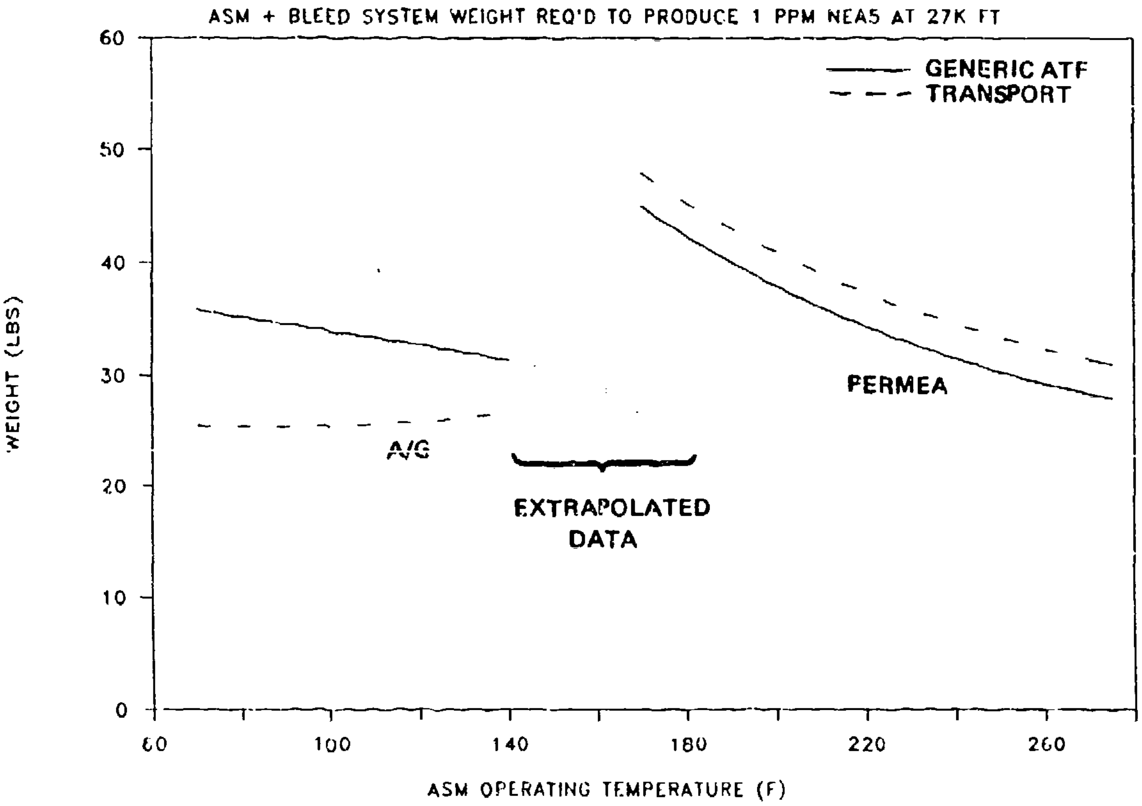


Figure 39. Benefits of Higher ASM Operating Temperatures

5.6 A/G Performance Sensitivity To Inlet Moisture

As discussed in Section 4.3, the A/G ASM exhibited some sensitivity to inlet moisture. This sensitivity was in the form of a few percent drop (5 percent for the specific conditions tested) in productivity under the highest inlet moisture conditions (180 grains which is equivalent to 120°F dew point). While a 5 percent drop in productivity is not a major problem, all possible factors affecting ASM performance should be considered. A plausible explanation for this performance drop can be developed based on an analysis of the partial pressure of air during these high moisture conditions. If one considers gas transport across the membrane fiber wall to be strictly a function of the differences in partial pressures of the individual gases on each side of the membrane, the performance change can be explained.

Table 19. A/G Moisture Sensitivity Analysis

Total pressures		Product flow (ppm)	Inlet moisture		Partial pressure of air		Comments
Inlet (psia)	Waste (psia)		Dew point (°F)	P_{H_2O} (psia)	Inlet (psia)	Waste (psia)	
44.70	14.63	0.211	-29.5	0.00	44.70	14.63	Dry
44.42	14.56	0.200	121.1	1.74	42.68	13.84	Saturated inlet
-	-	0.207	-	-	44.70	14.63	Product flow corrected to original pressures
Note: Partial pressure of air refers to partial pressure of all gases except water vapor							

Consider the two data points from the moisture tests presented in Table 19. The first point represents initial dry conditions while the second point represents saturated inlet air. Note that the product flow has dropped by 0.011 PPM from dry to saturated conditions. However, this can be explained by the fact that the ASM was actually operating at different inlet and waste pressures when considering only the partial pressures of air (obviously during dry conditions the partial pressure of air equals the total pressure). Using the performance model from Section 5.1, product flow was corrected back to the initial dry operating pressures as shown in Table 19 and explains most of the performance change.

This technique can be used by a designer to predict performance at any operating condition. It would follow that the largest impact on performance will be observed when the partial pressure of water vapor is the largest fraction of total inlet pressure.

5.7 A/G Water Separation Analysis

As is the case with general performance, the amount of moisture in the NEA was found to be a function of several variables. Realizing that the moisture content of the NEA may be of interest to an OBIGGS designer, who for example must concern himself with condensate in the high pressure compressor and storage bottles of a stored gas OBIGGS, a rough model of moisture separating performance was developed.

The derivation of this model is based on data presented in Section 4.3. First, the ratio of water vapor partial pressures in the NEA relative to the inlet is defined as the separation factor for water:

$$SEP_{water} = \frac{P_{water,\ NEA}}{P_{water,\ inlet}}$$

where: P_{water} = partial pressure of water vapor

As shown in Figure 40, it was found experimentally that SEP_{water} is independent of $P_{water,\ inlet}$ over the ranges tested or expected to be encountered in flight. Examination of the experimental data in Section 4.3 indicates that the NEA is very dry for most anticipated operating conditions and all but a few percent of the inlet water vapor passes through the membrane wall of the fibers into the waste flow. This fact allows the following approximation:

$$P_{water,\ waste} = \frac{P_{water,\ inlet}}{(1\text{-}Rec/100)Pr}$$

where: Rec = Recovery

Pr = Pressure ratio across fiber wall (Inlet Absolute/Waste Absolute)

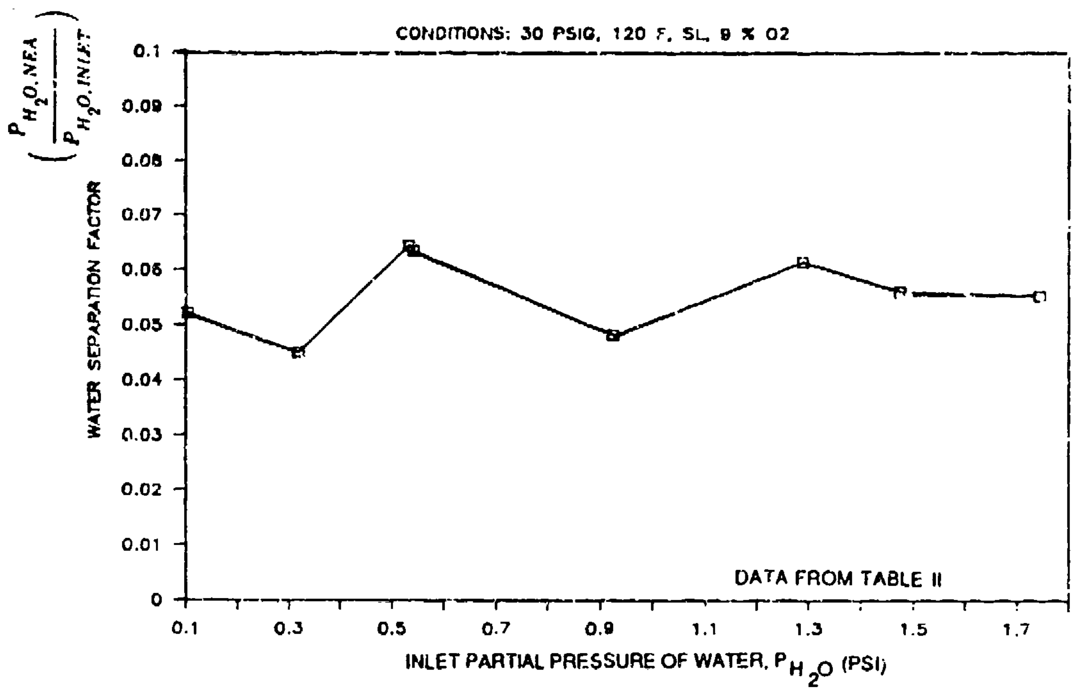
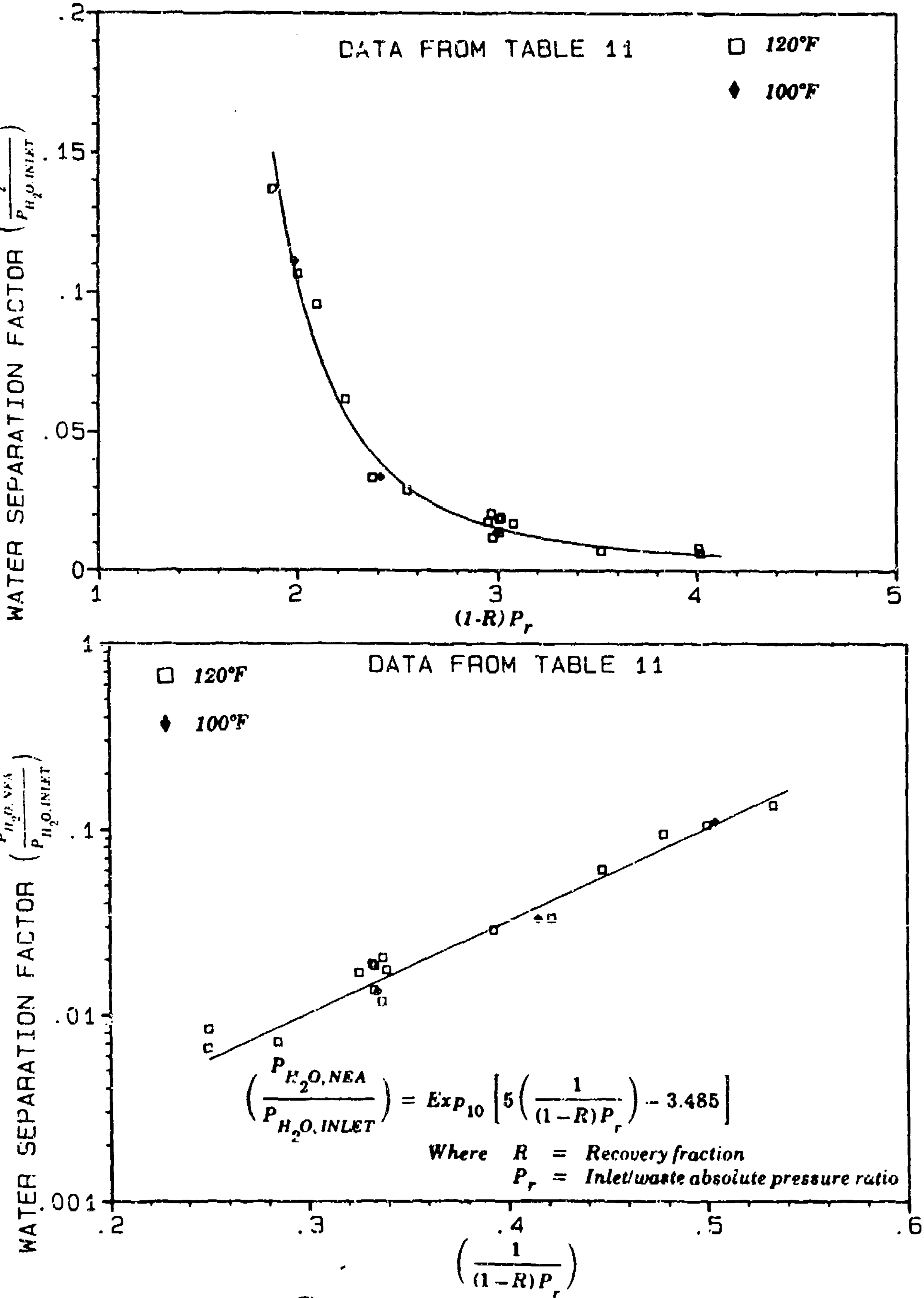


Figure 40. A/G Water Separation Versus Inlet Water Content

Since the transport of water vapor (or any gas) across the membrane wall is proportional to the difference in partial pressures, it can be reasoned that $P_{water, NEA}$ is limited by and therefore some function of $P_{water, waste}$. This in turn suggests:

$$SEP_{water} = f(1/(1\text{-}Rec/100)Pr)$$

This would imply that the separation factor is only a function of recovery and pressure ratio, regardless of inlet dew point, inlet pressure, altitude, oxygen concentration and temperature. Figure 41 shows all moisture separation data (from Section 4.3) plotted versus this recovery/pressure ratio term using both a linear and logarithmic scale. Considering the measurement problems, it is interesting to note that the data lie nearly in a straight line when plotted as the log of the separation factor versus the reciprocal of the recovery/pressure



$$\left(\frac{P_{H_2O,NEA}}{P_{H_2O,INLET}}\right) = Exp_{10}\left[5\left(\frac{1}{(1-R)P_r}\right) - 3.485\right]$$

Figure 41. A/G Water Separation Model

ratio term. This yields the following approximation for water separation performance:

$$SEP_{water} = Exp_{10}\ [5(1/(1-Rec/100)Pr)\ -3.485]$$

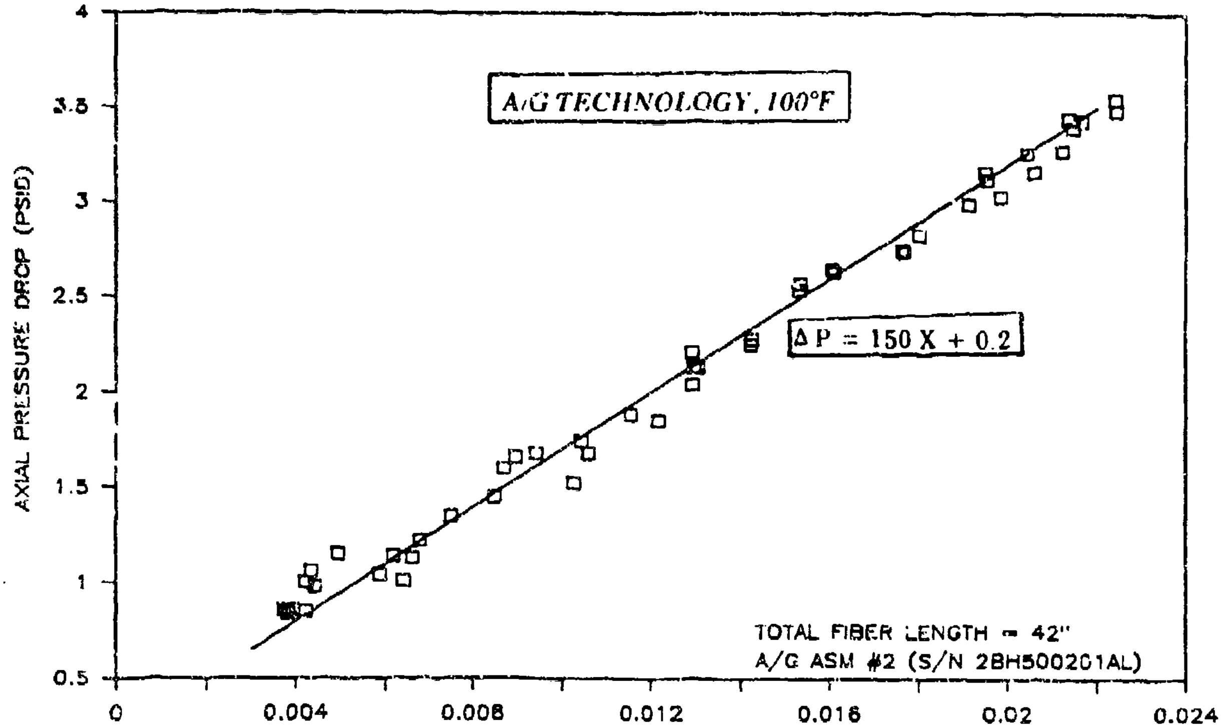
The above relationship should be valid for any size A/G ASM.

5.8 Fiber Axial Pressure Drop

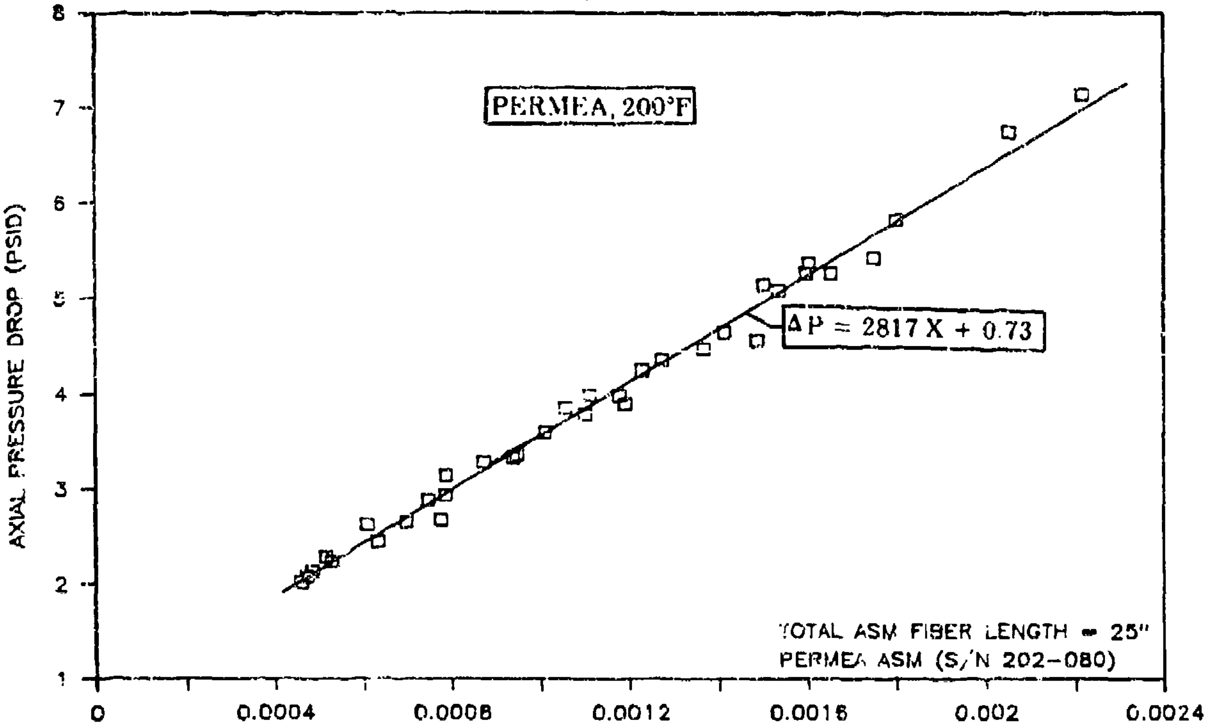
The ASM fiber axial pressure drop (bleed air inlet - NEA outlet) data are included as separate columns in the Appendix D and E performance data. The pressure drop has been characterized in Figure 42 for A/G ASM #2 and the Permea ASM at their typical operating temperatures. The pressure drop data for A/G ASM #1 varied by an insignificant amount from that shown for ASM #2. Pressure drop is nearly linear with NEA volumetric flow (NEA flow/Inlet Absolute Pressure) since the flow is actually laminar through the bore of each fiber (Reynolds Number is typically in the 100-200 range). A second term is included to account for waste flow which is essentially a function of the pressure difference across the fiber wall. Note that at zero NEA flow, some pressure drop will exist due to the waste flow down the bore of the fiber.

In general, the axial pressure drop is low for either unit, on the order of 3 PSID or less for most conditions of interest, and should not present a problem for OBIGGS applications. For example, at the specific operating conditions of NEA_5 at 50 PSIG, sea level, 100°F and 200°F (A/G and Permea), the pressure drop will be roughly 1.6 and 2.1 PSID for the A/G and Permea units respectively (less than 4 percent of the inlet absolute pressure). It is projected that ASMs four to five feet in length may be installed in future airplanes. While these ASMs will incur higher pressure drops, this should not present significant problems.

The data presented in Figure 42 should be general enough to provide pressure drop data for any design condition. For example, at high NEA flows (and high oxygen concentrations) extrapolation of this data should be acceptable. In order to apply this data to ASMs of varying length, these pressure drop data can be applied by multiplying delta P by the ratio of ASM fiber lengths (including the portion embedded in the tube sheet). ASMs of different diameters can be



$$X = \frac{W_{PRODUCT\,(PPM)}}{P_{INLET\,(PSIA)}} + \frac{P_{INLET\,(PSIG)}}{2.0 \times 10^4}$$



$$X = \frac{W_{PRODUCT\,(PPM)}}{P_{INLET\,(PSIA)}} + \frac{P_{INLET\,(PSIG)}}{4.08 \times 10^5}$$

Figure 42. Fiber Axial Pressure Drop Analysis

predicted using the ratio of the number of fibers (the number of fibers used in these particular ASMs is considered proprietary but may be obtained directly from the manufacturer). The following explicit expressions can be used to calculate fiber pressure drop for any size A/G or Permea ASM that utilizes the same fibers.

$$\Delta P = \left[150\left(\frac{W_{NEA}N_r}{P + P_{waste}} + \frac{P}{2.0 \times 10^4}\right) + 0.2\right]\left(\frac{L_{FIBER}}{42}\right)\left\{A/G\right\}$$

$$\Delta P = \left[2718\left(\frac{W_{NEA}N_r}{P + P_{WASTE}} + \frac{P}{4.08 \times 10^5}\right) + 0.73\right]\left(\frac{L_{FIBER}}{25}\right)\left\{PERMEA\right\}$$

where: ΔP = *Fiber Pressure Drop, PSID*

W_{NEA} = *NEA Flow Rate, PPM*

P = *ASM Inlet Pressure, PSIG*

P_{WASTE} = *ASM Waste Pressure, PSIA*

L_{FIBER} = *Total ASM Fiber Length, Inches*

N_r = *Ratio of the number of fibers in these test ASMs to the actual number of fibers.*

5.9 ASM Thermal Time Constants

The amount of time required for an ASM to change temperature will be of concern to an OBIGGS designer when considering such things as the time required to reach operating temperature. During the hot/cold start-up tests discussed in Section 4.4, the oxygen concentration data suggest an effective time constant of between 1 and 2 minutes. The actual ASM case temperature must be ignored because it lags behind the actual temperature of the fibers and will not accurately reflect performance. If the actual fiber warm-up is compared to a computed simple first order response (the actual thermal response appears to be at least second order) reasonable agreement can be obtained if the average inlet flow and weight of the fibers and one tube sheet are used, as follows:

$$\text{Thermal Time Constant} = \frac{\text{Weight (fibers + single tube sheet)}}{W_{\text{inlet (avg)}}}$$

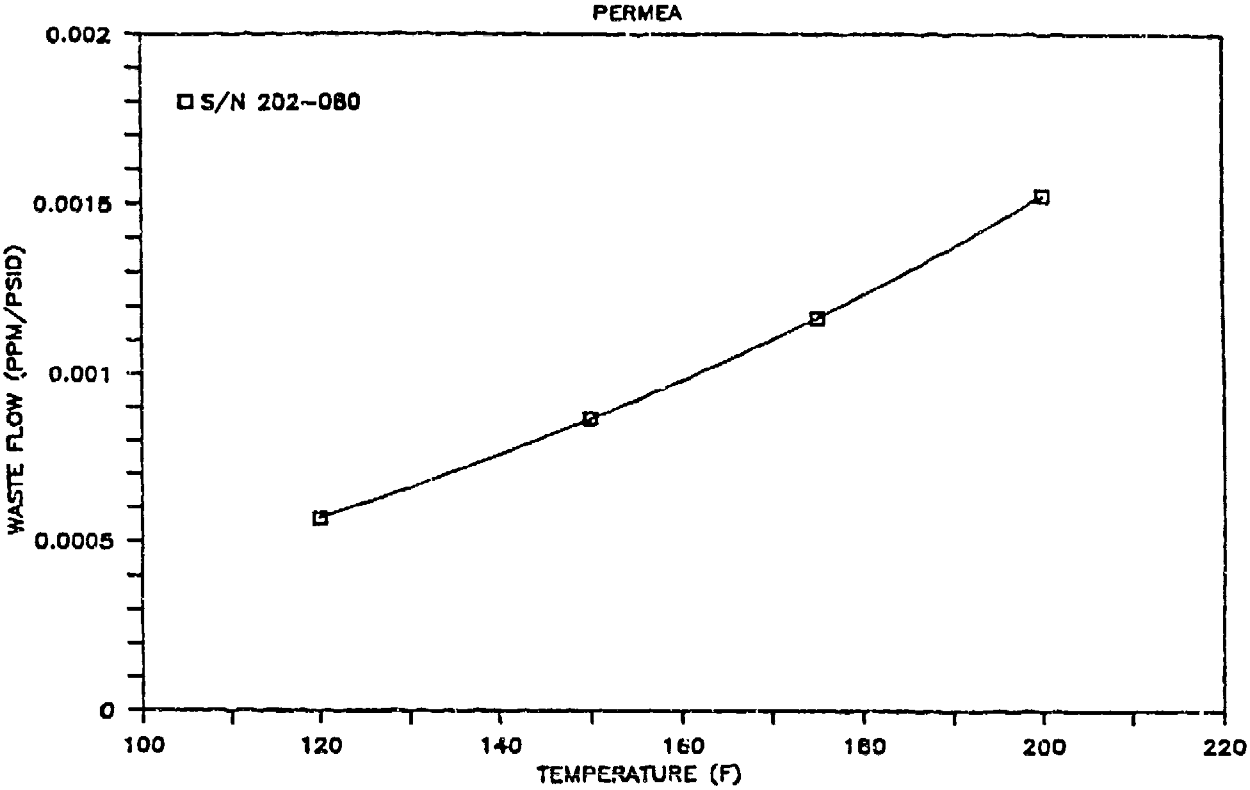
This modeling of thermal response, although rough, should prove reasonably accurate.

5.10 Simplified Waste Flow Analysis

Analysis of the performance data in Appendices D and E has shown that ASM waste flow is essentially a function only of temperature and pressure difference across the fiber wall. The effects of altitude are negligible and the effects of NEA flow are only significant at high NEA flow rates. This leads to a simplified model of waste flow presented in Figure 43 which shows waste flow to be directly proportional to the pressure difference across the fiber. This information can be applied to other ASMs using the same fibers by using the ratio of active fiber area or volume of active fibers to scale the waste flow.

This analysis of waste flow indicates that an ASM operating at full pressure will use a minimum amount of bleed flow regardless of the NEA flow. For example, if the ASM in a demand OBIGGS were not producing NEA during a climb, the waste flow would still remain at the same level as during periods of high NEA flow unless inlet pressure or number of on-line ASMs were reduced. Using the information presented in Figure 43, it is a simple matter to accurately determine waste flow at any inlet pressure and temperature.

Although this same information can be obtained through the models presented in Section 5.1, this analysis presents a greatly simplified method of estimating waste flow. A slightly more detailed model of Permea waste flow (used to estimate recovery at certain performance points) is presented in Appendix F.



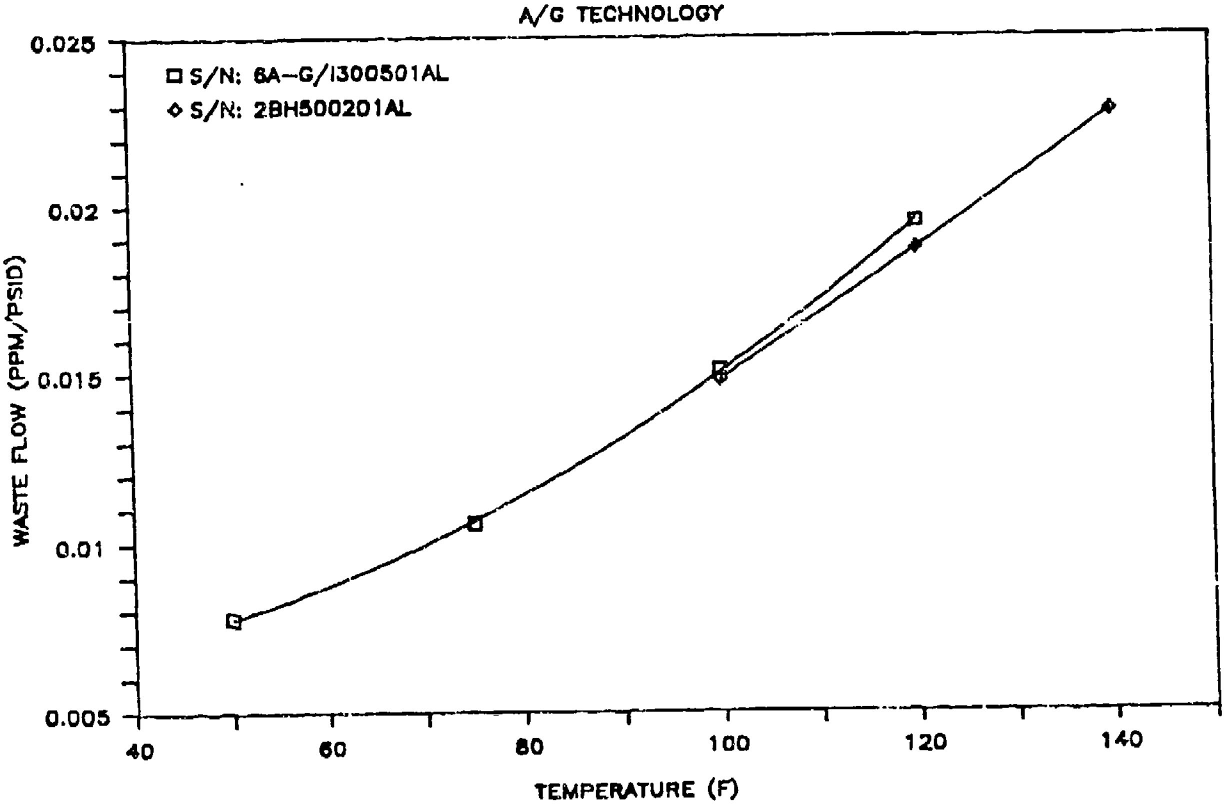


Figure 43. Simplified Waste Flow Analysis

5.11 Permea Performance Discrepancy

The endurance test data presented in Section 4.2.2 for the Permea ASM were accumulated entirely with the Permea Endurance Test Set-Up. As explained, this set-up produced a nonuniform temperature environment for the ASM. The temperature at the inlet was controlled to 200°F while heat transfer to ambient resulted in a nominal NEA outlet temperature of 178°F. The PERMEA unit was moved from the Primary Test Set-Up (constant temperature) to the Endurance Test Set-up (non-uniform temperature) at approximately 50 hours and then moved back to the Primary Test Set-Up at approximately 2050 hours. Comparison of performance at these operating conditions with data collected using the Primary Test Set-Up, with its constant temperature enclosure, is shown in Figure 44. Note the large discrepancy in initial performance between the two different set-ups.

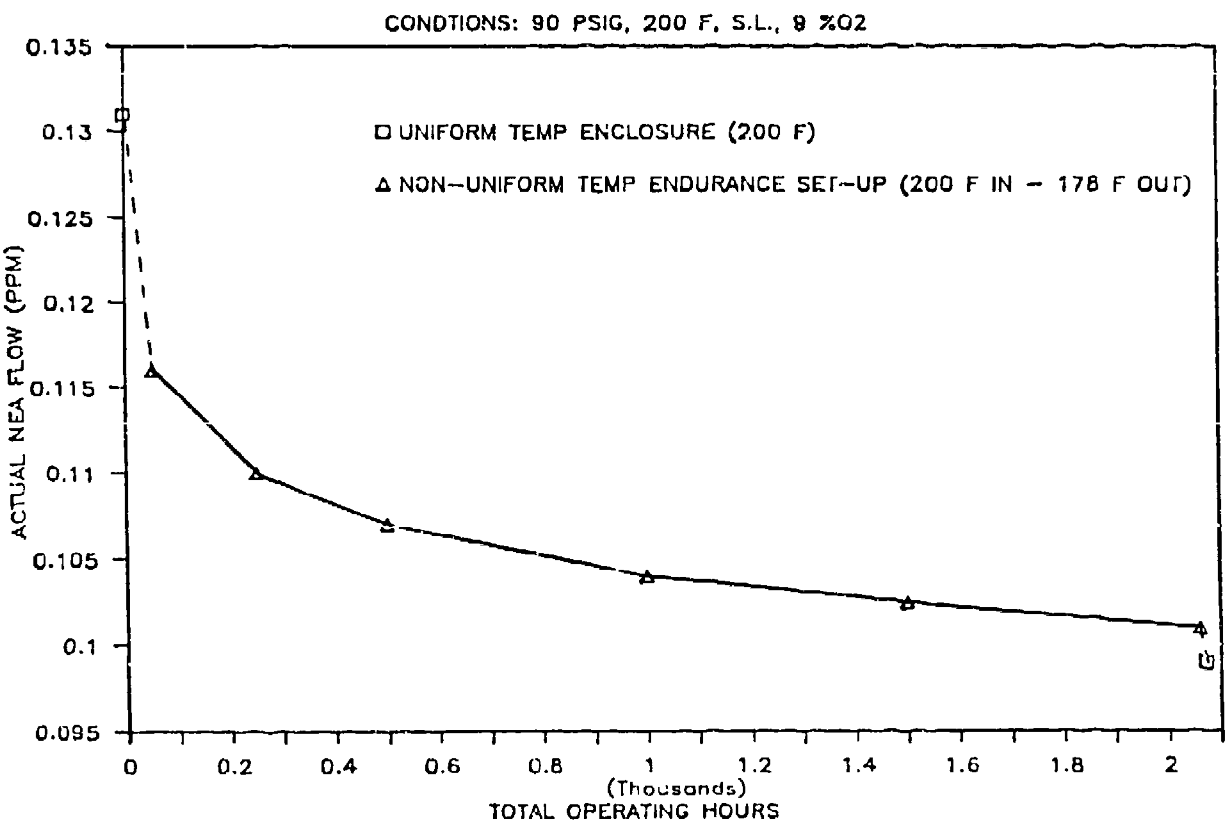


Figure 44. Permea Performance Discrepancy

This discrepancy was recognized at the beginning of the endurance test but at the time was attributed to the nonuniform temperature environment. However, at the conclusion of the endurance testing the ASM was retested in the Primary Test Set-Up and as can be seen in Figure 44 did not regain a significant amount of performance, but in fact, a slight (1 percent) additional performance drop was observed. If the initial performance discrepancy were due to nonuniform temperatures, then a similar discrepancy should also have been observed when the ASM was transferred back to the Primary Test Set-Up; the ASM should have regained roughly the same performance delta.

In an attempt to eliminate any doubt about instrumentation, the NEA flow meters used in the two different set-ups were operated in series and found to indicate within 3 percent of reading for the ranges encountered during the endurance test. The performance discrepancy (0.166 PPM vs. 0.131 PPM) represents approximately an 11 percent drop and therefore can not be explained by instrumentation uncertainty.

If instrumentation is eliminated as a possible source of the discrepancy and the data are accepted as valid, then a significant performance shift occurred between the first measured performance point in the Endurance Set-Up and the last previously measured point using the Primary Set-Up. This initial decline was unexpected based on the previous tests using the Primary Set-Up.

Since the Endurance Set-Up was new, the possibility exists that an anomalous event may have occurred during start-up. Possible events could include over pressurization or over temperature when the ASM was first operated in the Endurance Set-Up. However, the ASM was protected with a 100 PSI inlet relief valve as well as an inlet temperature controller and an independent 220°F temperature limiter. These safeguards, coupled with close observation during initial start-up virtually preclude these possibilities. Nevertheless, inspection of the data in Figure 44 shows the initial decline to be inconsistent with the trends during the remainder of the endurance test.

An additional possibility exists that the ASM was contaminated during initial start-up of the Endurance Set-Up. Even though a filter was installed on the ASM inlet, the electric heater and inlet pressure gage were positioned between the filter and ASM (See Figure 5 schematic), leaving open the possibility that the heater or pressure gage could have been a source of unfiltered contamination. Although the heater was new and had appeared to be clean, deposits on the heating elements could have been vaporized during start-up and transported into the ASM. The pressure gage (a bourdon tube type) was also new and could have contained oil from a calibration device such as a dead weight tester. However, a specific close inspection of the gage was performed prior to installation to identify this very problem and no evidence of oil was detected.

During the post-test inspection of the ASM, Permea reported finding liquid oil on the waste side of the ASM (outside of the fibers and on the inside of the fiberglass shell). Some evidence of oil on the inlet side was also reported but the majority of oil was found on the waste side. The total quantity of liquid oil remaining in the separator was estimated by Permea at approximately one teaspoon and was present on fibers occupying approximately 25 percent of the fiber bundle cross section. After receiving Permea's report of oil in the ASM, a close inspection of the waste tubing used in the endurance test also revealed the presence of oil. However, no evidence of oil could be found on any inlet tubing or pipe fitting (heater and inlet pressure gage included), leaving the source of the liquid oil undetermined.

While the source of this oil can not be determined, it appears that the only satisfactory explanation for the performance discrepancy is the unexplained introduction of liquid oil into the ASM. The inlet tube sheet seal problem, reported during the subsequent high temperature tests, may have actually began during this time and allowed the oil to migrate past the seal into the waste side of the ASM. The nature of the seal failure was that of initial leakage during start-up followed by an abrupt "seating" a few seconds later. It is possible that the seal problem began earlier than initially thought but not detected. If the separation process actually occurs across the thin membrane on the outside of the fiber, then the presence of oil at this point could significantly interfere with that separation process. Permea indicated that there was no evidence of oil on the interior or bore side of the fibers.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The primary goal for this program of demonstrating at least a factor of ten improvement in ASM weight was met or exceeded. Continued membrane technology development will make permeable membrane ASMs superior in every respect to older technology ASMs.

Compared to previous laboratory experiences with earlier prototype ASMs (molecular sieve from Clifton Precision and permeable membrane from DOW Chemical), the performance and reliability of the A/G and Permea advanced ASMs were markedly superior.

The following conclusions were drawn from the A/G Technology ASM tests:

- The performance and packaging of the A/G unit were such that the ASM may be considered flight worthy without further modifications with the possible exception of the crack experienced in the tube sheet seal.

- The A/G unit exhibited fast warm up in simulated arctic conditions and quick response for short high speed descents.

- While operating on high dew point inlet air, the A/G unit produced relatively dry NEA containing only a few percent of the moisture in the inlet air.

- Although a slight drop in performance was observed with the A/G unit during high inlet moisture conditions, returning to dry inlet conditions restored lost performance.

- No problems were encountered with the A/G unit during vibration tests and results suggested that membrane units in general should present no vibration problems.

- The A/G unit exhibited no sensitivity to on/off cycling when quick opening valves were positioned and operated immediately upstream.

- No problems were encountered with the A/G unit from thermal shock during the hot/cold start-up tests, even with a -60°F arctic start.

- No problems were encountered with the A/G unit during short term exposure at 140°F.

- The A/G unit was fairly sensitive to oil vapor present in the test air supply, loosing productivity at the rate of 10 percent per 1000 hours. When this vapor was removed with carbon filters, the rate of degradation was reduced to 2 percent per 1000 hours.

The following conclusions were drawn from the Permea ASM tests:

- The relatively high operating temperature and high efficiency of the Permea ASM reduced its bleed air cooling penalty.

- The high operating temperature of the Permea unit may preclude the need for a liquid water extractor or coalescer filter.

- The Permea unit was operated for over 2000 hours at 200°F and for a short time at 250°F. The unit suffered a 14 percent loss in productivity during the 2000 hour endurance test and 25 percent overall. The majority of the performance loss occurred in the first few hundred hours, after which the rate of degradation was reduced to 3 percent per 1000 hours. However, liquid oil may have been introduced into the ASM and therefore could possibly be responsible for part or all of the observed degradation.

- Removal of the inlet carbon filter during the second half of endurance testing did not increase the rate of degradation, suggesting that the Permea unit was insensitive to oil vapor in the test air supply. However, if liquid oil was actually introduced into the ASM, any sensitivity to oil vapor may have been masked.

- Operation of the Permea unit at 250°F improved productivity by approximately 40 percent reducing efficiency by only 3 percent compared to operation at 200°F.

When making comparisons between the A/G and Permea ASMs, two factors should be kept in mind. First, the A/G ASM was of a much larger scale, having about 8 times the NEA flow capacity of the Permea ASM and utilized relatively light packaging. Therefore any scale-up analysis is a much smaller jump for the A/G unit than for the Permea. Secondly, the intent of this program is not only to evaluate specific ASMs from A/G Technology and Permea, but to also extrapolate the potential of this technology into the future. In that regard, even though the Permea unit was relatively small and heavy, analysis indicates that it may be competitive with the A/G unit, on a total airplane penalty basis, under certain conditions.

While the A/G ASM is projected to be lighter than the Permea ASM, Permea's use of bleed air at a lower flow rate and higher temperature will result in lower bleed system weight penalties. As a result, Permea's combined ASM plus bleed system weight penalties may be comparable to and in certain cases less than those of the A/G unit. However, while the ASM weight estimates are of reasonably high confidence, predicted bleed system weight penalties have a lower confidence factor.

Bleed air penalties for any ASM will be reduced significantly when ASM operating temperatures are high enough (roughly 160°F or above for ATF like fighter) to allow bleed air cooling with fuel.

While the advanced ASMs offer definite weight reductions compared to molecular sieve technology, the volume of these systems will be roughly the same due to the molecular sieve's relatively high bulk density. Therefore, advanced ASM technology is not expected to yield significantly smaller packages.

Operating pressure is one of the most significant factors affecting the size and weight of an ASM. Every effort should be made to operate the ASM at the highest available pressure. Nevertheless, while the advanced membranes offer their greatest weight savings at relatively high bleed pressures (50 to 100 PSIG), the savings will still be significant at pressures as low as 20 PSIG.

The bleed air contamination encountered during actual airplane operation may be greater or less than that of the test air supply, sufficient data are not available to reach a conclusion.

6.2 Recommendations

Future membrane technology improvements should target reductions in overall airplane weight penalties and not focus exclusively on only one aspect, such as ASM weight. The A/G Technology unit can most effectively achieve further reductions in overall penalties by increasing operating temperatures and membrane efficiencies. The Permea unit, on the other hand, will best reduce these overall penalties by reducing ASM weight.

Membrane suppliers should pursue manufacturing capabilities that will allow the production of light weight ASMs of varying diameters in order to match different flowrate applications without bundling several smaller ASMs together.

Both A/G and Permea units experienced problems with tube sheet seals. The crack experienced in the bond between tube sheet and outer case of A/G ASM #2 suggests that their design may be sensitive to stresses in this area and could benefit from the use of a flexible seal. Furthermore, the importance of a flexible seal may increase with diameter. The Permea unit, which already utilizes a flexible seal, would require seals compatible with higher temperatures if that operating regime is explored.

The use of inlet air carbon filters should be seriously considered until bleed air quality can be assured. The need for good inlet particulate filters is an absolute necessity. Further, the military airplane community should begin formal investigations into bleed air quality over the life of airplane engines "in-the-field" and not just for new engine qualification.

The operation of both A/G Technology and Permea ASMs should be explored at higher temperatures with the goal of reducing overall airplane penalties. Analysis suggests that higher temperature operation of the A/G ASMs may not be worthwhile if recovery continues to fall off at higher temperatures. Therefore, A/G Technology should explore recovery improvements along with higher temperatures. A definite payoff is indicated for Permea if operation at temperatures above 200°F is feasible. Further long term tests of any ASM operating at elevated temperatures must be conducted before the feasibility of such operation can be assumed.

The next step in membrane based ASM development should be complete transition of this technology to DoD airplanes. This may be best accomplished by building a flight worthy and fully qualified membrane based ASM for a specific airplane application. Proof testing should proceed with a realistic ground simulation followed by actual flight testing.

Degradation of ASMs for stored gas versus demand OBIGGS should be compared. In a stored gas system the ASMs would be continually subjected to any bleed air contamination and the ASM diameters may be smaller. In a demand system, the ASMs could be "ganged" such that some of the modules would be subjected to bleed air contamination for only brief time periods.

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ACRONYMS AND ABBREVIATIONS

ACFM	Actual Cubic Feet per Minute
ASM	Air Separation Module
ATF	Advanced Tactical Fighter
CRT	Cathode Ray Tube
DoD	Department of Defense
DOE	Department of Energy
ECS	Environmental Control System
HX	Heat Exchanger
ID	Inside Diameter
IGG	Inert Gas Generator
In	"
Lbs	Pounds
LN_2	Liquid Nitrogen
Min	Minute
MS	Molecular Sieve
MSIGG	Molecular Sieve Inert Gas Generator
NEA	Nitrogen Enriched Air
NEA_5	Nitrogen Enriched Air at 5 percent O_2
NEA_9	Nitrogen Enriched Air at 9 percent O_2
OBIGGS	On-Board Inert Gas Generator System
OBOGGS	On-Board Oxygen Gas Generator System
OD	Outside Diameter
OEA	Oxygen Enriched Air
PM	Permeable Membrane
PPM	Pounds Per Minute or Parts Per Million
PMIGG	Permeable Membrane Inert Gas Generator
PSA	Pressure Swing Adsorption
PSIG	Pounds Per Square " Gage
PSIA	Pounds Per Square " Absolute

APPENDIX A - A/G Technology Final Report

ADVANCED AIR SEPARATION MODULES
FOR
AIRCRAFT OBIGGS

A/G TECHNOLOGY CORPORATION
34 Wexford Street
Needham, MA 02194

September 9, 1987

Prepared under
Boeing Aerospace Company
Purchase Contract GK9030
as a Subcontract under
US Air Force Prime Contract F33615-84-C-2431

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

ASM	-	Air Separation Module
ATF	-	Advanced Tactical Fighter
BMAC	-	Boeing Military Aircraft Company
F	-	Degrees Fahrenheit
LPM	-	Liters Per Minute
NEA	-	Nitrogen Enriched Air
PPM	-	Pounds Per Minute
PSI	-	Pounds Per Square Inch
SCFM	-	Standard Cubic Feet Per Minute
OBIGGS	-	On-Board Inert Gas Generation System

1.0 INTRODUCTION

1.1 Background

On-Board Inert Gas Generation System (OBIGGS) technology is under consideration by the US Air Force for aircraft fuel tank fire protection. Given the demands placed on modern military aircraft, it is essential that the OBIGGS add minimum weight and occupy minimum space, while providing efficient and reliable nitrogen production.

Under Contract to the USAF, Boeing Military Aircraft Company (BMAC), issued an RFQ for procurement and testing of advanced Air Separation Modules (ASM's) for inerting applications offering at least a 10-fold reduction in weight and volume over current technology. Based on a prior, independent assessment by BMAC, the most promising technology for achieving these goals and realizing a workable OBIGGS is based on the advanced permeable membranes of A/G Technology Corporation (1).

Current OBIGGS technology centers on two alternative approaches: Permeable Membranes and Molecular Sieves for separation of air into a nitrogen enriched blanketing stream and an oxygen enriched vent stream. Permeable membranes have the inherent advantage of improved reliability over molecular sieve units since they do not require rapid cycling automatic valves for regeneration. Furthermore, permeable membrane systems have higher efficiencies at the scale of operation envisioned for OBIGGS than molecular sieve units, resulting in lower feed air requirements.

Permeable membranes developed by A/G Technology Corporation demonstrated the potential for order-of-magnitude reductions in weight and volume versus both permeable membrane and molecular sieve current technology on the basis of actual separating material employed for equal flow and concentration conditions (1). Additionally, since the A/G Technology advanced permeable membranes are internally pressurized, the need for a pressure vessel is eliminated. The resultant tube sheet encasing weight is also an-order-of-magnitude lower than conventional technology.

Because of the projected weight and volume reduction, the A/G Technology advanced permeable membranes offer the potential of a direct flow OBIGGS, versus the presently envisioned stored gas systems for some aircraft. The advent of a direct flow OBIGGS will eliminate the heavy storage tanks, complex compressor and bulky piping associated with the stored gas concept and thus greatly improve system reliability.

1.2. Objective and Approach

In response to the BMAC RFQ L-1403-OOET-699, A/G Technology Corporation provided two hollow fiber advanced permeable membrane cartridges for evaluation testing at the BMAC WPAFB Test Office, as well as, engineering support services for data analysis and cartridge post test evaluation. These cartridges were sized to be relatively close to the projected ASM space requirements of an ATF-like airplane. Each cartridge was to provide a nominal 0.25 pounds per minute (PPM) of Nitrogen Enriched Air containing 5% oxygen (NEA5) under operating condition of 60 psig, 100 F.

The overall BMAC test program, including pressure cycling, temperature cycling, vibration testing, moisture exposure and life testing of the units is detailed elsewhere in this report. The A/G Technology Corporation program consisted of pre-shipment baseline testing of the units, consultation and engineering support throughout the test program and post-test evaluation of the one unit returned to A/G Technology.

The oxygen/nitrogen separation (e.g., selectivity) and productivity (e.g., permeability) characteristics of the advanced hollow fiber permeable membranes incorporated in the cartridges provided to BMAC were chosen to match the anticipated NEA5 requirements of an ATF-like airplane. A complete mission profile for the ATF-like airplane, or OBIGGS requirements for other aircraft may dictate either higher or lower nitrogen concentrations. Furthermore, the NEA purity requirement of a demand system may be in the NEA8 to NEA10 range. In the demand system case, membrane productivity improvements may override selectivity considerations.

Productivity is defined as the volume of NEA produced per permeable membrane unit area. The higher the productivity, the smaller the ASM. Efficiency is the ratio of NEA produced to the feed air flowrate. The higher the efficiency, the lower the bleed air requirements for the OBIGGS.

It is important to note that the advanced permeable membrane technology developed by A/G Technology can be tailored within a reasonable range to meet preferred performance based on a tradeoff analysis covering:

- Bleed Air Flowrate and Pressure Requirements
- Bleed Air Precooling Requirements
- NEA Concentration
- ASM Size (i.e., NEA Productivity).

Thus, if improved efficiency (reduced bleed air requirement) is desirable, this can be achieved with some loss in NEA productivity and slightly increased ASM size. Conversely, higher productivity with reduced efficiency can be achieved. By providing a more selective/lower permeability membrane, it should be possible to operate at higher temperatures (reduced cooling) with the loss in intrinsic membrane permeability balanced by higher productivity at the increased bleed air temperature.

1.3 Summary

Both A/G Technology units demonstrated performance equal to or better than their projected performance and were operated at pressure and temperature combinations higher than the baseline conditions of 60 psig/100 F without problem. The first unit tested was performance mapped over a wide range of pressure, temperature, altitude and NEA concentrations, then subjected to temperature cycling, pressure cycling, vibration testing and life testing. The second unit underwent some performance mapping followed by an extended life test which was still in progress at the time of this report.

Typical performance improvement on a weight basis by the A/G Technology advanced permeable membrane units versus the Dow baseline performance was 20-fold higher. Over the set of conditions tested this improvement ranged from 10 to 25-fold.

The units were uneffected by cold (-60 F) and warm (140 F) starts, on/off pressure cycling and vibration testing. The units were successfully operated at temperatures up to 120 F, 20 degrees higher than anticipated, without any change in baseline performance. At a temperature in the order of 120 F heat removal systems become much more simple than the refrigerative cooling devices required for operation below 80 F. Savings in cooling requirements above 120 F are less dramatic and may not be significant in an advanced permeable membrane OBIGGS tradeoff analysis.

The units were also operated at pressures of 90 psig without change in baseline performance. In fact the first cartridge evaluated was operated at test conditions of both 70 psig/120 F and 90 psig/100 F without problem.

An unexpected, non-representative oil vapor contamination in the BMAC Test Facility air supply resulted in a performance loss of less than 10% on the first unit during a 500 hour life test. This excessive contamination is not expected in the normal operation of an OBIGGS, but having occurred, would affect any high permeability, advanced permeable membrane cartridge in the same fashion. After this contamination problem was identified, activated carbon prefilters were installed and the second unit was life tested. The second unit was sucessfully operated for 1,300 hours with no discernible performance loss (2).

2.0 ADVANCED PERMEABLE MEMBRANE ASM DESCRIPTION

The ASM's provided to BMAC were fabricated to commercial air separation cartridge design and standards and, as such, were not militarized. Although minor changes in ASM construction are envisioned to meet the specialized needs of the military, no major changes were identified from the BMAC WPAFB tests.

A schematic drawing of an A/G Technology advanced permeable ASM is provided in Figure A-1. Referring to the figure, a multitude of hollow fiber membranes are arranged in parallel within a cylindrical enclosure. The enclosure is chemical and temperature resistant, high strength polysulfone. The hollow fibers are sealed at both ends within the enclosure with an epoxy potting compound. Polysulfone end fittings are bonded at each end and on the sides of the enclosure to provide mating flanges for feed air inlet, NEA outlet and to vent oxygen enriched "waste gas".

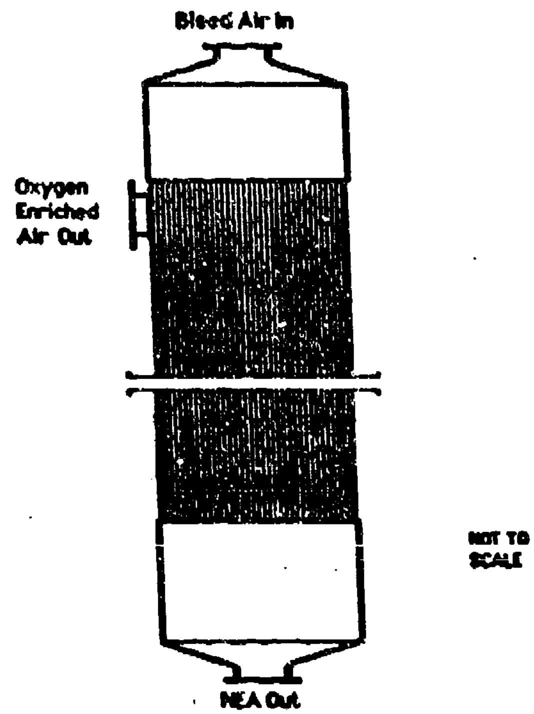

Figure A-1. Simplified Sketch of A/G Technology Advance Permeable Membrane ASM

The nominal physical characteristics of the ASM's provided to BMAC are:

Cartridge Diameter:	3 in
Cartridge Length:	43-5/8 in
Cartridge Weight:	4.1 lbs
Tube Sheet Diameter:	2.56 in

The ASM cartridge weight breakdown is nominally:

Fiber protective Casing*:	50%
Membrane Fibers:	33%
Potting Compound:	9%
Feed, Product, Waste Ports:	8%

* NOTE: This enclosure is based on commercial pressure requirements and is overdesigned for anticipated OBIGGS operating conditions. Thus, lighter-weight enclosures are possible.

3.0 PRE-SHIPMENT PERFORMANCE TESTING

The two ASM units were baseline performance tested prior to shipment to WPAFB. Test conditions used for these cartridges were:

Serial Number	Condition	Inlet Pressure	Temperature
6A-G/I300501AL	1	60 psig	78 +/- 2 F
	2	60 psig	108 +/- 2 F
	3	90 psig	80 +/- 2 F
2BH500201AL	1	60 psig	74 +/- 2 F
	2	60 psig	110 +/- 2 F
	3	90 psig	74 +/- 2 F

NEA flowrate and NEA efficiency data for each cartridge over this range of test conditions are presented in Figures A2 through A9.

4.0 POST WPAFB EVALUATION PERFORMANCE TESTING

One ASM (Serial Number 6A-G/I300501AL) was returned to A/G Technology for a performance assessment at the conclusion of the WPAFB testing. This cartridge, as detailed in the BMAC Report, was inadvertently subjected to a non-representative air feed contaminated by oil vapor. Post-test evaluation included baseline

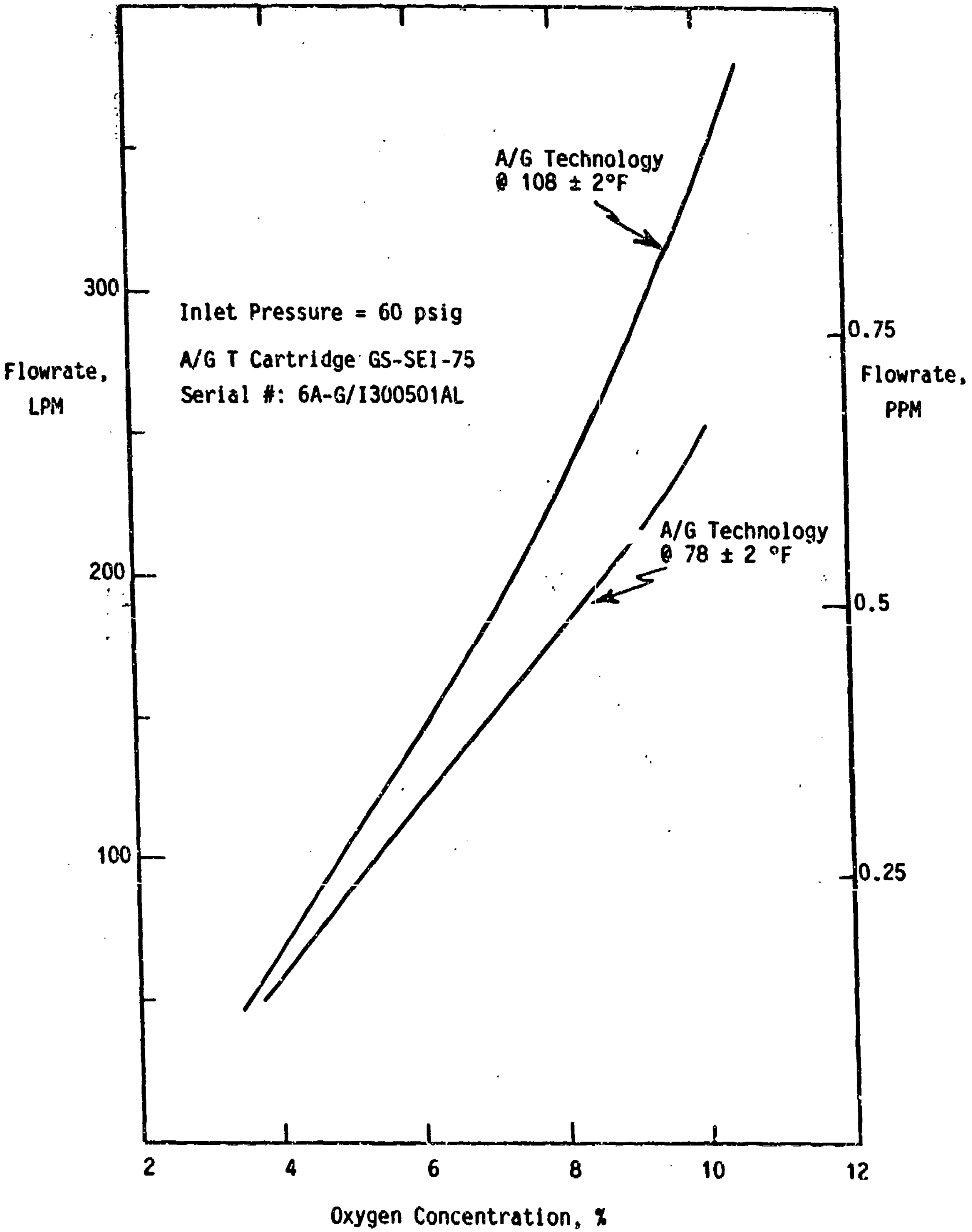

Figure A-2. NEA Flowrate versus Oxygen Concentration and Temperature at 60 psig Inlet Pressure.

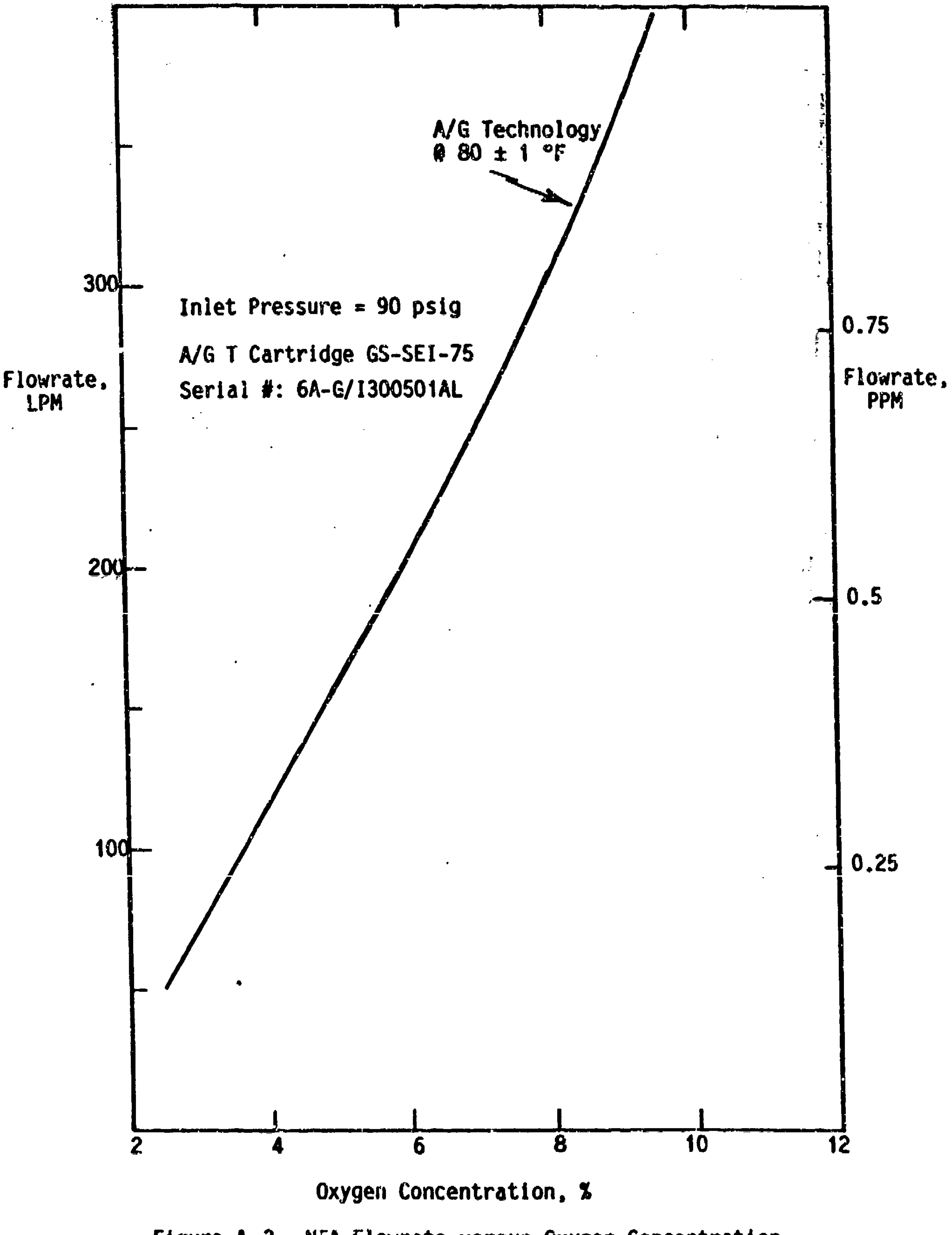

Figure A-3. NEA Flowrate versus Oxygen Concentration at 90 psig Inlet Pressure.

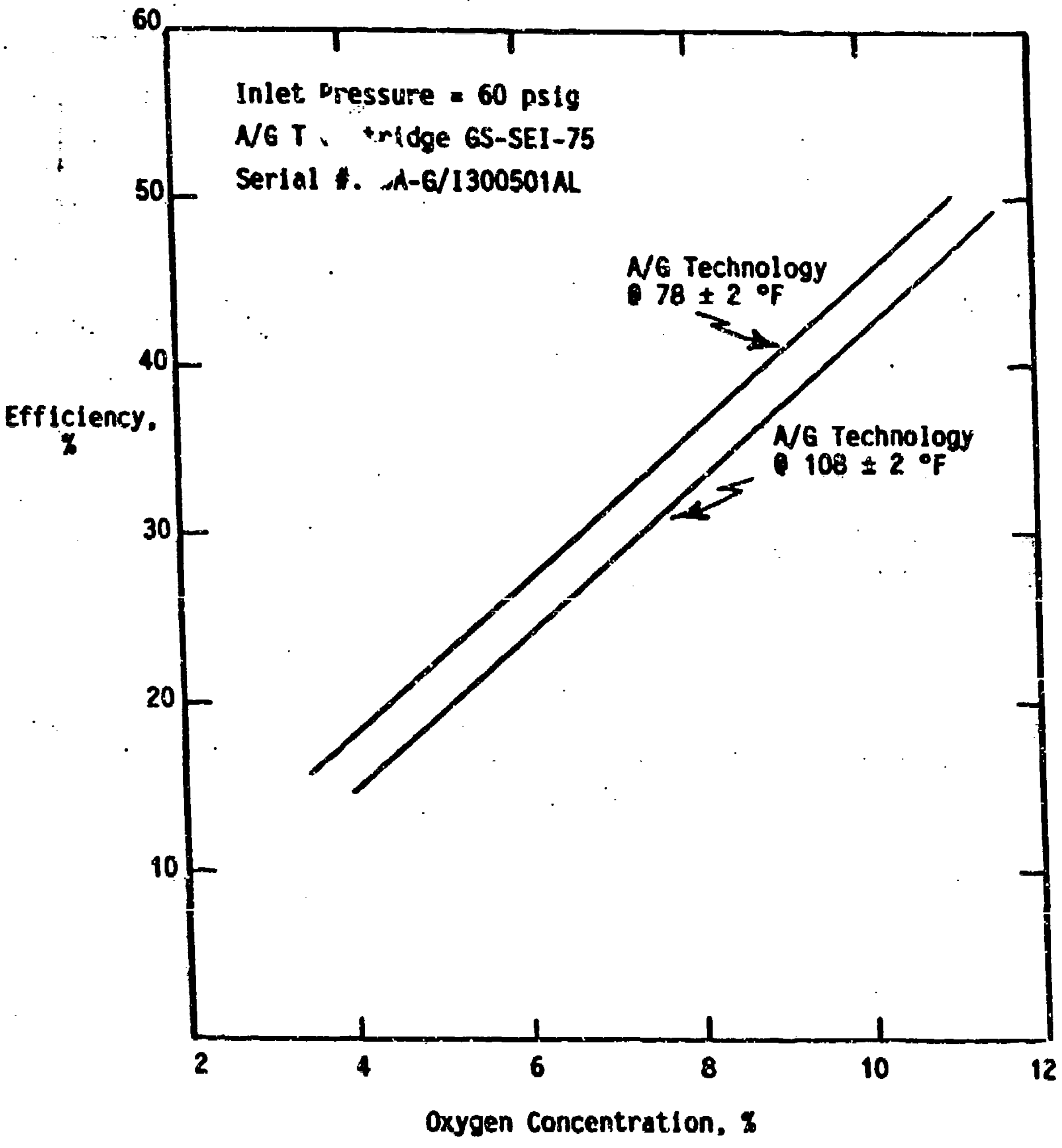

Figure A-4. NEA Efficiency versus Oxygen Concentration and Temperature at 60 psig Inlet Pressure.

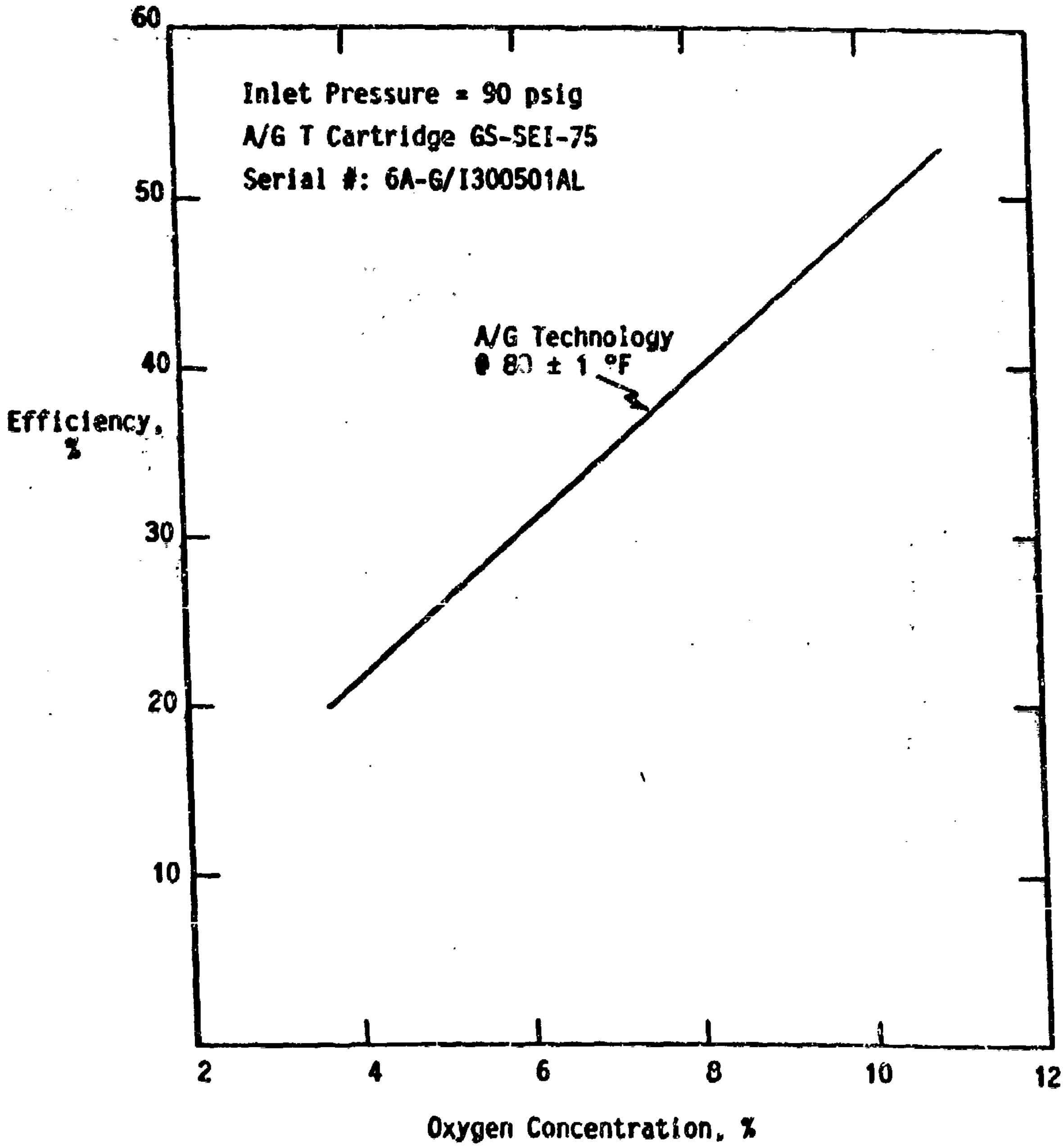

Figure A-5. WEA Efficiency versus Oxygen Concentration at 90 psig Inlet Pressure.

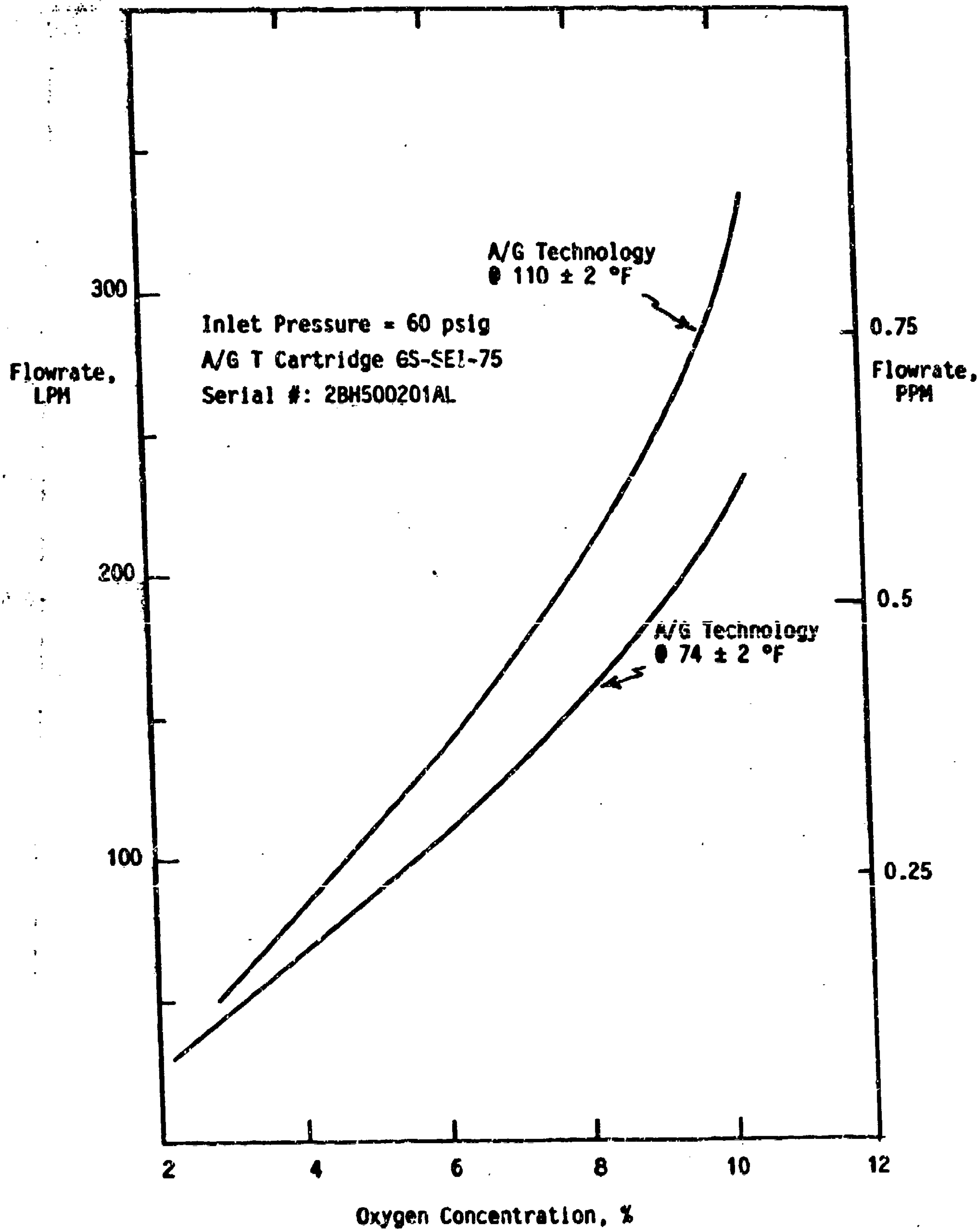

Figure A-6. NEA Flowrate versus Oxygen Concentration and Temperature at 60 psig Inlet Pressure.

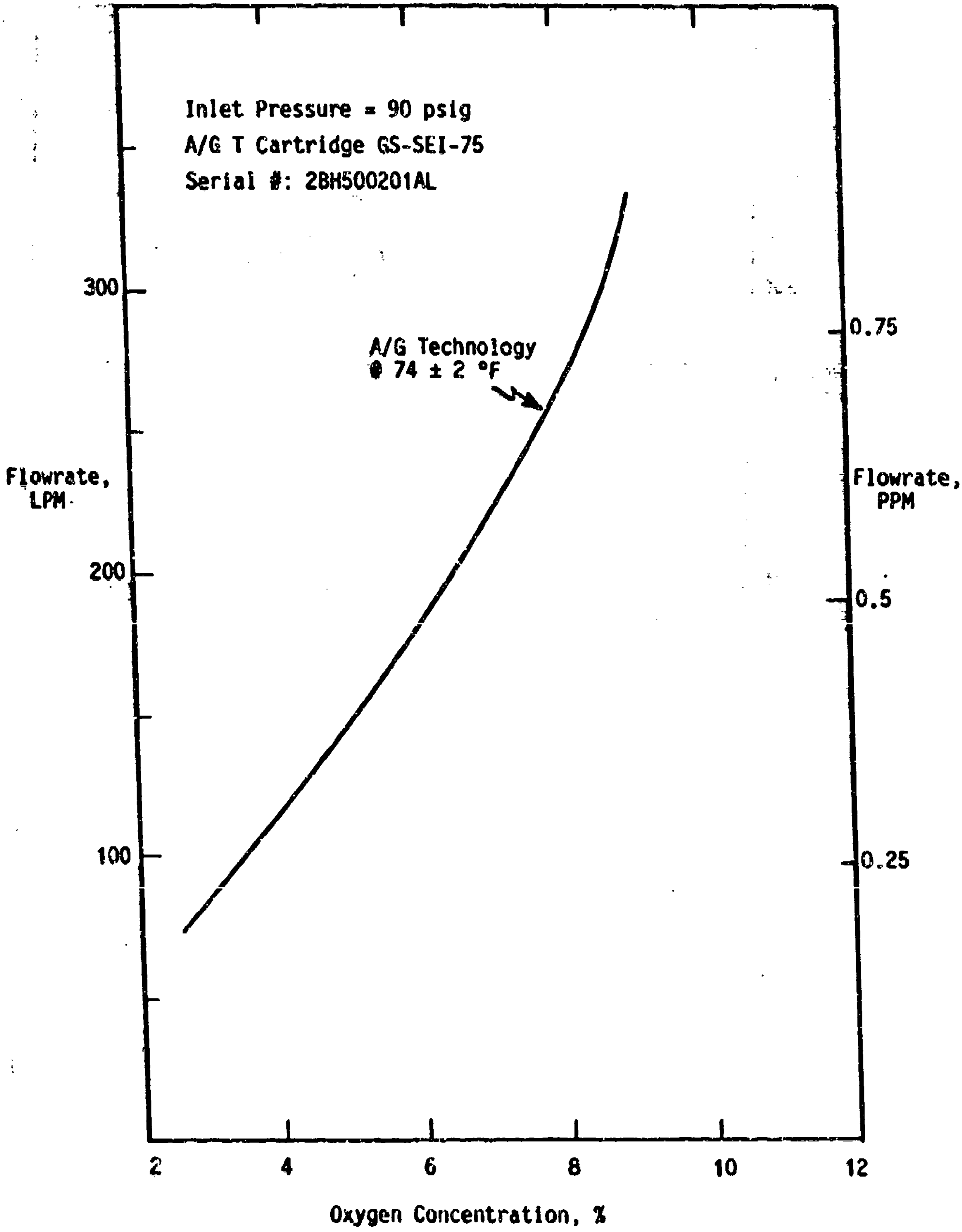

Figure A-7. NEA Flowrate versus Oxygen Concentration at 90 psig Inlet Pressure.

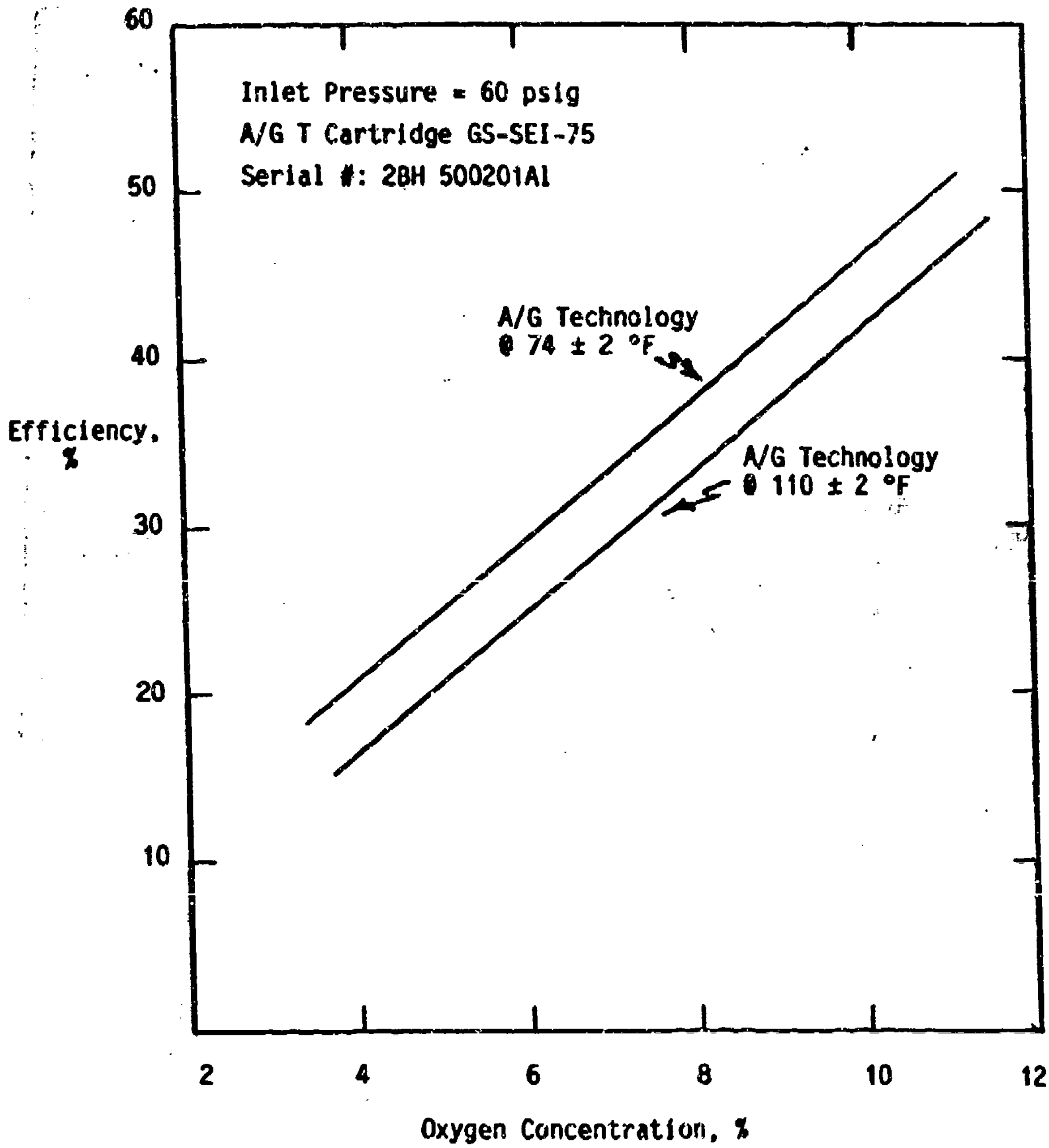

Figure A-8. NEA Efficiency Versus Oxygen Concentration and Temperature at 60 psig Inlet Pressure.

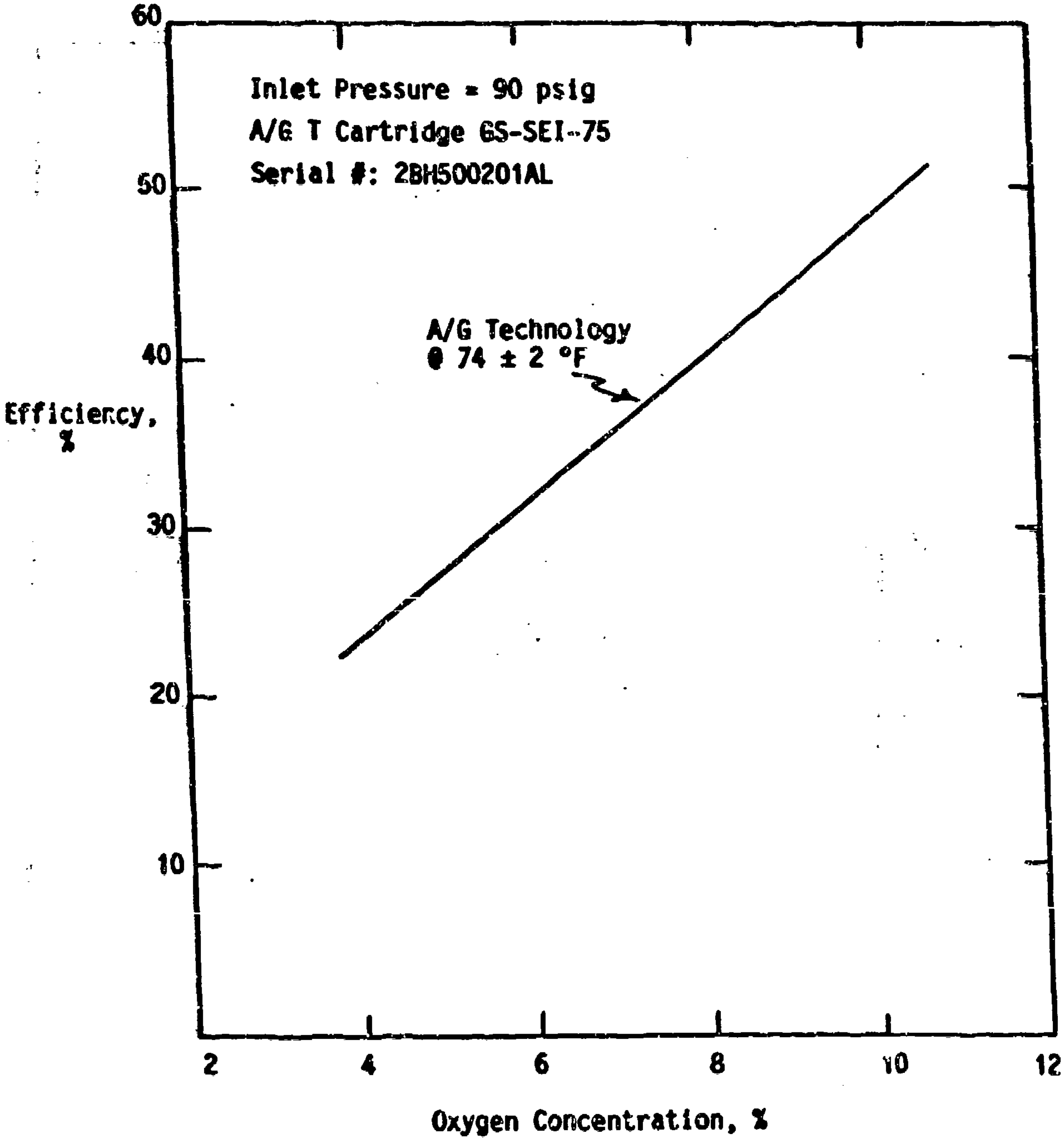

Figure A-9. NEA Efficiency versus Oxygen Concentration at 90 psig Inlet Pressure.

performance testing and an attempt to recondition the unit to original performance by soaking in a surfactant solution.

At the start of post-test evaluation, the cartridge gave off an offensive odor which persisted excessively through more than 12-hours of clean air flushing. The odor was eventually reduced, but never eliminated.

Baseline performance data of the cartridge as shipped, as received after the WPAFB tests and after reconditioning are presented in the following table. These data are at 60 psig inlet pressure:

	As Shipped	As Received After WPAFB Testing	After Surfactant Cleaning
NEA Flow (LPM)	85.8	70.8	70.8
NEA Concentration (%)	5.0	5.5	5.6
Efficiency (%)	22.4	23.0	23.9
Temperature (F)	78	65	65

As can be observed, the unit underwent a modest performance loss due to the oil vapor deposition on the high permeability membrane. Although the surfactant solution appeared to remove some contamination, based on a color change in the solution, the cartridge performance was not materially affected.

In independent tests, A/G Technology advanced permeable membrane cartridges tested for oxygen generation (as opposed to NEA production) have been operated with an oil compressor (Dayton Speedaire Model 2Z499B, 1 hp) for over 3,600 hours without any change in performance (3). In these tests, which were still in progress as of this date, a 0.2 micron microporous membrane prefilter was the only pretreatment; a carbon adsorption cartridge for oil vapor removal was <u>not</u> employed.

Initial baseline data and performance data after 3,624 hours of operation are as follows:

Time (hours)	Oxygen Enriched Air Flowrate (SCFH)	Oxygen Concentration (%)
0	21.8	34.9
3,624	21.7	34.5

The minor differences in performance are well within the experimental error of the instrumentation used during these tests. This stable performance further supports the non-representative nature of the BMAC compressor air contamination.

Available details of the compressor oil in this extended duration test are given in Figure A-10.

5.0 MATHEMATICAL MODELING

A mathematical model of advanced permeable membrane performance has been developed based on preliminary test data from the BMAC Test Office in order to facilitate advanced permeable membrane OBIGGS performance predictions in a quick and simple manner. This model reflects the consistent relationships observed between NEA concentration and NEA efficiency as functions of feed air compression ratio and temperature. The critical equations in the model are provided below. Given that the permeability of individual gases follows an Arrhennius Plot with respect to temperature dependence, it was logical to look for a power series to express the relationship.

Membrane permeation coefficient, K_p, in units of SCFM/psi is modeled by the expression:

$$K_p = 2.63 \times 10^{-3} \; T^{0.959} \qquad [1]$$

where,

T = Temperature, F

The NEA efficiency, η, as a function of compression ratio and NEA oxygen concentration is:

$$\eta = 6.4 \ln(P_r - 2.4) + 4.5C_R - 1.8 - ((T - 50)/12.5)^{1.3} \qquad [2]$$

where,

P_r = Compression ratio
C_R = Oxygen concentration in NEA

The Permeate (i.e. waste gas) flowrate, F_P (SCFM) is defined as:

$$F_P = K_p \times DP \qquad [3]$$

where,

DP = Differential pressure, psig

Material Safety Data Sheet
May be used to comply with OSHA's Hazard Communication Standard, 29 CFR 1910.1200. Standard must be consulted for specific requirements.

U.S. Department of Labor
Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

IDENTITY (As Used on Label and List): Air Compressor Oil #42988

Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.

Section I

Manufacturer's Name: Moraine Oil Company, Inc.	Emergency Telephone Number: (414) 567-7523
Address (Number, Street, City, State, and ZIP Code): 1212 W. Second Street, Oconomowoc, Wisconsin 53066	Telephone Number for Information: (414) 567-7523
	Date Prepared: Revised 04/01/87
	Signature of Preparer (optional)

Section II — Hazardous Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity; Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits Recommended	% (optional)
refined mineral oil (base oil)	oral 15 g/kg			92
additive package for anti-wear and detergent - dispersant containing zinc, phosphorus and calcium				

Section III — Physical/Chemical Characteristics

Boiling Point 760 mm Hg	725° F	Specific Gravity (H_2O = 1)	.87
Vapor Pressure (mm Hg.)	Low	Melting Point	unknown
Vapor Density (AIR = 1)	Less than 1	Evaporation Rate (Butyl Acetate = 1)	Less than 1

Solubility in Water: negligible

Appearance and Odor: brown, slightly oily odor

Section IV — Fire and Explosion Hazard Data

Flash Point (Method Used)	Flammable Limits	LEL	UEL
Cleveland open cup 440° F		unknown	unknown

Extinguishing Media: use dry chemical foam, carbon dioxide or water foam

Special Fire Fighting Procedures: use water to cool fire exposed containers

Unusual Fire and Explosion Hazards: water may cause frothing, treat as a petroleum product fire.

(Reproduce locally) OSHA 174, Sept. 1985

Figure A-10. Available Details of Compressor Oil Used in Extended Duration Life Tests Conducted at A/G Technology Corporation

And the NEA flowrate, F_R (SCFM), is therefore:

$$F_R = \frac{F_P}{(1 - \eta)} \times \eta \qquad [4]$$

$$= \frac{\eta}{(1 - \eta)} K_p \times DP \qquad [5]$$

This model should be updated to reflect any changes in, or additions to, the preliminary data provided to A/G Technology.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The extensive independent testing performed by BMAC has demonstrated the ability of the A/G Technology advanced permeable membranes to provide better than a 10-fold weight advantage over the baseline (Dow) membrane units. The units exhibited excellent environmental resistance to moisture and temperature and maintained complete physical integrity throughout pressure cycling, temperature cycling and vibration testing. Long term performance testing on non-representative, oil vapor contaminated air resulted in a less than 10% performance loss over a 500 hour period. The level of contamination was excessive and not realistic of an OBIGGS bleed air supply.

It should be noted that high productivity, advanced permeable membranes are, by nature, more sensitive to feed air contamination than previous generation membranes. This is expected to be valid regardless of the membrane base polymer or the membrane manufacturer. Thus, reasonable precaution should be taken in feed air prefiltration. Nonetheless in-house testing by A/G Technology has shown no detrimental effects on membrane performance for advanced permeable membrane cartridges operated with mineral-based oil lubricated compressors, even without carbon adsorption pretreatment.

Long term testing of the second unit on clean air for over 1,300 hours, proved the contaminated air testing to be an anomaly, with no discernable performance change throughout the clean air life test (2).

The A/G Technology advanced permeable OBIGGS performed well at 120 F feed air temperatures. This is 20 F higher than originally expected for performance mapping. Based on this performance and the exposure of the units to temperatures as high as 140 F without problem, continuous operation within the range of 120 to 160 F should be possible. This higher temperature operation would reduce bleed air cooling requirements and further reduce OBIGGS system weight and volume, depending on the NEA quality required.

6.2 Recommendations

The exceptional performance demonstrated by the A/G Technology advanced permeable membrane units warrants further testing and evaluation of these devices for OBIGGS. It is recommended that:

1. Multiple advanced permeable membrane units be tested in parallel to achieve an ASM package that matches the inert gas requirements of an ATF-like airplane. Header design and module arrangements could then be optimized and very accurate weight and volume requirements for the entire ASM could be determined.

2. Engineering studies be conducted to determine if any substantial weight and/or volume reductions would result from increased permeable membrane cartridge diameters versus the current 3-inch diameter. If significant reductions can be achieved, a program should be initiated to develop a larger diameter unit.

3. OBIGGS design reviews consider the tradeoffs between bleed air temperature/precooling requirements, ASM size, NEA quality and bleed air flow requirements (ASM efficiency).

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2. Anderson, C. L., BMAC Test Facility, WPAFB, Personal Communication, July 31, 1987.

3. A/G Technology Test Data, Internal Communication, September, 1987.

APPENDIX B - Summary of ASM Technology Survey Results

This information is excerpted from:

Anderson C.L., "Advance On-Board Inert Gas Generator System Technology Assessment," Interim Report, Contract F33615-84-C-2431, May 1985.

Note that the information is dated May 1985 and the present status of membrane developments are likely to be significantly changed.

ADVANCED MEMBRANE TECHNOLOGY COMPARISON
(Information Dated May 1985)

Company Name	Potential Specific Performance Improvement[1]	Estimated Probability of Success[2]	Need For Financial Help[3]	(PPM) NEA_5/NEA_9 per Lb of Fibers	(PPM) NEA_5/NEA_9 per Ft^3 of Fibers	Operating Pressure (PSIG @ S.L.)	Operating Temp (°F)	Efficiency (%)	Comments
DOW	1X (Baseline)	Existing	N/A	.013/.033	.26/.66	85	75	25%/35%	Better fibers- only in planning stage.
A/G Technology	11.5X	E	A	.15/.32	2.7/6.1	50 (Can go higher)	70 (140 Max)	23%/36%	Small 3/4" dia. cartridges now in existence.
Albany Corp.	3X	E	B	.039/-	.69/-	100	110 (170 Max)	32%/-	Now producing industrial NEA systems for Union Carbide.
Applied Membrane Technology	~3X	U	B	-	-	40-100	100	52%	Very preliminary R&D program. Asymetric hollow fiber membranes.
Bend Research Inc.	No Data	-	-	-	-	-	-	-	No data available before report deadline.
Envirogenics Systems Co.	.7X	E	A	.009/-	.23/-	375	100 (120 Max)	60%	Now producing industrial OEA systems. Spiral-wound flat-plate membranes.
Fluid Systems Div of UPO	2X	E	A	.025/-	.22/-	100	(135 Max)	10%/-	Now producing industrial OEA systems. Spiral-wound flat-plate membranes.
Monsanto	1X	G	B	.012/-	.29/-	50	225	23%	Membrane is projected within 1 yr. Now producing industrial NEA systems.
Separex	< 1X	-	-	-	-	-	-	-	Heavier & bulkier than DOW's. Spiral-wound, flat-plate membranes.

1 Specific Performance Improvement = Lbs/Min NEA_5 per Lb Fibers compared to DOW fibers
2 E-Excellent/G-Good/F-Fair/P-Poor/U-Unknown
3 A - Will not be developed in near future without help
B - Already being developed without Air Force assistance

ADVANCED PSA TECHNOLOGY COMPARISON

(Information Dated May 1985)

Company Name	Potential Specific Performance Improvement[1]	Estimated Probability Of Success[2]	Need For Financial Help[3]	(PPM) NEA_5/NEA_9 per Lb of Sieve	(PPM) NEA_5/NEA_9 per Ft^3 of Sieve	Operating Pressure (PSIG @ S.L.)	Operating Temp (°F)	Efficiency (%)	Comments
Clifton Precision	1X (Baseline)	N/A	N/A	.0087/ .018	.42/.87	40	75 (40-150)	14%/28%	Union Carbide 4A Sieve. Aircraft units available now.
Cryomec	17X	P	A	.15/-	6/-	Unknown	Unknown	33%/-	Carbon sieve with rotating wheel. Not yet demonstrated on any scale.
Sunstrand (Bergbau Forschung)	1X	G	B	.0083/-	.23/-	100	50-130	29%/-	Carbon sieve. Industrial systems available now.
University of Cincinnati	4.5X	P	A	-/.081	-/-	No Data	No Data	84%	Organometallic Complex. Basic research required (High Risk).
Zwick Energy Research	4-5X	U	A	No Data	No Data	No Data	No Data	No Data	Ideas only, to improve Union Carbide 4A Sieve.

1 Specific Performance Improvement = Lbs/Min NEA_5 per Lb Fibers compared to Clifton Precision System (Using Union Carbide 4A Sieve)

2 E-Excellent/G-Good/F-Fair/P-Poor/U-Unknown

3 A - Will not be developed in near future without help

B - Already being developed without Air Force assistance

APPENDIX C - Mass Flow Measurement Equations

Sonic Nozzles:

The equations used to calculate mass flow through the inlet and product sonic nozzles were based on NASA Technical Note D-2565. The basic form is as follows:

$$W = \frac{P\ A\ (Corr_{EXP})\ C^{*}\ C_d\ (60)}{\sqrt{T^{o}_{R}}} \sqrt{\frac{R_{AIR}}{R_{NEA}}}$$

where: W = Mass flow, PPM or lbs/min.

P = Nozzle inlet total pressure, PSIA.

A = Nozzle throat area, IN^2.

$Corr_{EXP}$ = Area correction for thermal expansion of nozzle throat.

C^* = Critical flow function per NASA D-2565.

C_d = Discharge coefficient per NASA D-2565.

R_{AIR} = Gas constant for air = 53.3497.

R_{NEA} = Gas constant for NEA = 55.15 - 0.08618 ($\%O_2$).

T = Nozzle inlet total temperature, ^oR.

The nozzle inlet pressure is actually measured as static pressure. However, the inlet piping is large compared to the throat, A/A_* was no greater than 20 for any nozzle which yields a maximum P_t/P = 1.0006 (per NACA 1135). This implies a maximum error of 0.06%, which was ignored, and P_{static} was therefore assumed equal to P_{total}.

The nozzle throat diameters, used for the A/G and Permea tests, were measured to the nearest 0.0001" at room temperature. The measurements were as follows:

ASM Under Test	Nozzle Throat Dia. (IN)	
	Inlet	Product
A/G	0.0685	0.1367
Permea	0.0362	0.0564

The nozzles were operated at temperatures as much as 50°F off room ambient. To correct for thermal expansion of the nozzles (brass nozzles), the following correction was used:

$$Corr_{EXP} = (A'/A) = (d'/d)^2 = (1 + C_{EXP}\,\Delta T)^2 = [1 + 1.11\times10^{-5}(T_{°F} - 70)]^2$$

The critical flow function, C^*, accounts for real gas effects as follows:

$$C^* = 0.532 + [1.48\times10^{-5} + 1.086\times10^{-7}\,(70 - T_{°F})]P_{PSIA}$$

The discharge coefficient, C_d, is approximated by the following:

$$C_d = 0.99738 - \frac{3.3058}{\sqrt{N_R}}$$

where: N_R = Throat Reynolds Number = $\dfrac{0.02122\,W_{PPM}}{d_{IN}\,\mu}$

μ = Viscosity

$= 1.018\times10^{-6} + 1.46\times10^{-9}\,(T_{°F} - 70)\ lb_m/sec\text{-}in$

Since C_d is dependent on W, an iterative solution for W was used with an initial guess of 0.99 for C_d.

Added to the sonic nozzle flow calculation for the product flow only was 0.0125 PPM for oxygen analyzer flow.

Rotameters:

The rotameters used to measure waste and product flow for the Permea endurance test were factory calibrated and specified as ± 2 % accurate. They were further corrected to actual conditions as follows:

$$W = W_{INDICATED}\sqrt{\frac{P_{amb}}{14.7} \times \frac{1}{S.G.}}$$

where: $S.G. = \left(\frac{535}{T_{°R}}\right)(0.981)$ for 9 $\%O_2$ product

$S.G. = \left(\frac{535}{T_{°R}}\right)(1.015)$ for 30 $\%O_2$ waste

APPENDIX D - A/G Technology Performance Envelope Data

This Appendix includes actual measured performance data for both of the A/G Technology ASMs (ASM #1 and ASM #2) presented in tabular and graphical form.

The definitions for the tabular data column headings are as follows:

- PASMIN = ASM inlet pressure, PSIG.
- PWASTE = ASM waste pressure, PSIA.
- T-ASM = ASM case temperature, ^{o}F.
- WPROD = Product or NEA mass flow rate, PPM or Lbs/Min.
- OXPROD = Product or NEA O_2 concentration, % by volume.
- O/I = Recovery or product flow/inlet flow, %.
- DP-ASM = ASM pressure drop or inlet - product pressure, PSID.
- WINLET = ASM inlet mass flow rate, PPM or Lbs/Min.
- TASMIN = ASM inlet air temperature, ^{o}F.

The data on the following pages is organized according to the temperature and waste pressure. Each page contains all data (product flows and inlet pressures) collected at a particular temperature and waste pressure. The following index is offered to aid in locating specific data.

A/G ASM #1 (S/N 6A-G/I300501AL)

A/G ASM #2 (S/N 2BH500201AL)

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

120°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.02	14.71	121.9	0.100	9.01	20.45	0.95	0.490	119.8
20.04	14.69	121.8	0.200	11.80	33.77	1.31	0.593	119.9
20.05	14.67	121.8	0.299	13.56	43.23	1.67	0.693	119.9
19.98	14.68	121.9	0.399	14.75	50.41	2.04	0.791	120.0
29.91	14.71	121.3	0.100	6.08	14.72	0.98	0.681	119.0
29.98	14.70	121.3	0.200	8.38	25.30	1.27	0.791	119.2
29.99	14.69	121.3	0.300	10.14	33.53	1.54	0.896	119.1
30.00	14.68	121.4	0.401	11.50	40.16	1.85	0.998	118.9
29.95	14.67	121.6	0.600	13.45	49.84	2.44	1.203	119.8
40.11	14.66	122.0	0.100	4.65	11.08	1.04	0.901	120.0
40.00	14.71	121.9	0.199	6.35	19.77	1.26	1.008	120.1
40.01	14.69	121.9	0.301	7.88	26.99	1.51	1.114	120.1
39.90	14.67	121.9	0.400	9.19	32.91	1.73	1.214	119.9
39.95	14.69	121.9	0.600	11.21	42.19	2.27	1.422	119.4
40.16	14.68	121.8	0.800	12.66	49.38	2.73	1.620	118.8
55.02	14.71	121.2	0.100	3.54	8.37	1.05	1.193	120.1
54.84	14.70	121.2	0.200	4.70	15.33	1.25	1.307	120.3
55.04	14.70	121.1	0.300	5.86	21.11	1.51	1.422	120.3
54.99	14.68	121.1	0.400	6.98	26.18	1.67	1.528	120.4
54.76	14.71	121.2	0.600	8.87	34.58	2.06	1.736	120.0
55.00	14.67	121.2	0.801	10.36	41.23	2.47	1.942	119.1
54.93	14.67	121.3	1.000	11.54	46.77	2.86	2.138	118.5
69.95	14.69	120.9	0.099	3.02	6.68	1.09	1.490	120.1
70.12	14.65	120.8	0.200	3.78	12.41	1.24	1.609	120.2
70.02	14.68	120.8	0.299	4.68	17.34	1.58	1.726	120.5
69.95	14.68	120.8	0.400	5.54	21.80	1.76	1.836	120.5
69.97	14.67	120.8	0.600	7.16	29.14	1.90	2.058	120.5
70.10	14.67	121.0	0.799	8.53	35.29	2.29	2.263	119.8
70.05	14.66	120.9	1.001	9.69	40.71	2.65	2.459	118.7
69.98	14.66	120.9	1.199	10.65	44.98	2.97	2.666	118.5

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

120°F, Nominal 5 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.01	4.98	121.1	0.101	5.61	21.00	1.30	0.479	119.4
20.05	5.00	121.2	0.201	8.51	34.29	1.80	0.585	119.7
20.00	4.99	121.2	0.299	10.63	43.83	2.32	0.681	119.9
19.89	4.97	121.3	0.400	12.23	51.29	2.87	0.781	120.1
30.02	5.00	121.4	0.100	3.77	14.76	1.24	0.680	120.2
30.08	5.00	121.3	0.200	5.81	25.27	1.62	0.791	120.3
29.93	5.02	121.4	0.301	7.62	33.70	2.01	0.895	120.3
30.08	5.00	121.4	0.400	9.06	40.14	2.37	0.998	120.3
29.92	4.96	121.6	0.599	11.31	50.04	3.15	1.197	120.2
40.05	4.99	121.5	0.100	3.08	11.38	1.22	0.880	120.0
40.06	4.97	121.6	0.199	4.47	20.17	1.52	0.988	119.9
39.96	4.94	121.6	0.300	5.92	27.52	1.82	1.091	119.8
40.01	4.96	121.5	0.400	7.21	33.40	2.10	1.198	119.8
40.09	5.01	121.6	0.599	9.29	42.62	2.73	1.404	119.6
40.04	5.00	121.5	0.801	10.88	49.85	3.33	1.607	119.6
54.88	4.99	121.4	0.100	2.60	8.62	1.19	1.158	119.8
54.94	5.00	121.3	0.200	3.52	15.76	1.41	1.270	119.8
54.93	5.00	121.3	0.301	4.56	21.76	1.63	1.382	119.9
54.85	5.02	121.3	0.400	5.59	26.86	1.87	1.490	119.9
55.02	4.98	121.1	0.600	7.39	35.16	2.30	1.706	119.8
55.12	5.01	121.0	0.800	8.89	41.72	2.85	1.918	119.8
55.10	4.97	120.9	1.000	10.10	47.19	3.33	2.119	119.5
69.97	5.00	120.9	0.099	2.43	6.89	1.21	1.444	120.2
69.97	5.00	120.9	0.199	3.10	12.79	1.35	1.558	120.2
70.14	4.96	120.7	0.300	3.88	17.88	1.57	1.675	120.5
70.01	4.96	120.7	0.400	4.70	22.43	1.77	1.784	120.5
70.06	4.98	120.7	0.600	6.30	29.95	2.12	2.005	120.5
70.01	4.96	120.7	0.799	7.67	36.07	2.51	2.217	120.5
70.19	4.98	120.8	1.000	8.82	41.17	2.93	2.429	120.2
70.01	4.96	120.8	1.200	9.82	45.68	3.33	2.627	119.9

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

100°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.57	14.69	100.1	0.101	9.05	25.06	0.75	0.402	98.8
20.25	14.68	100.1	0.200	12.28	40.01	1.08	0.500	98.8
20.12	14.67	100.3	0.300	14.15	50.13	1.40	0.599	98.9
19.98	14.68	100.3	0.400	15.41	57.56	1.74	0.695	98.9
30.06	14.69	100.5	0.101	6.03	18.29	0.76	0.551	98.8
30.00	14.68	100.5	0.200	8.84	30.56	1.03	0.654	98.8
30.00	14.68	100.6	0.301	10.81	39.71	1.28	0.757	98.6
30.05	14.70	100.5	0.401	12.25	46.64	1.55	0.859	98.6
30.05	14.70	100.6	0.600	14.20	56.58	2.10	1.060	98.7
40.16	14.68	100.4	0.101	4.36	14.38	0.76	0.699	98.6
39.99	14.71	100.4	0.201	6.59	24.86	0.98	0.808	98.5
39.95	14.69	100.4	0.300	8.40	32.83	1.20	0.914	98.7
40.02	14.69	100.3	0.400	9.83	39.23	1.43	1.019	98.5
39.96	14.68	100.4	0.600	11.95	48.98	1.90	1.225	98.5
39.94	14.70	100.3	0.799	13.41	56.08	2.33	1.425	98.4
54.99	14.68	100.2	0.100	3.17	10.78	0.77	0.931	98.5
55.04	14.70	100.2	0.201	4.64	19.33	0.94	1.042	98.6
54.87	14.67	100.1	0.301	6.08	26.16	1.26	1.149	98.8
55.01	14.67	100.1	0.400	7.34	31.76	1.33	1.260	99.0
55.01	14.67	100.1	0.600	9.38	40.63	1.69	1.476	99.2
55.02	14.72	100.1	0.799	10.92	47.36	2.05	1.686	99.3
55.10	14.71	100.4	1.001	12.05	52.77	2.47	1.896	99.6
69.99	14.71	100.1	0.101	2.55	8.67	0.80	1.171	100.4
69.94	14.70	99.9	0.200	3.56	15.57	0.93	1.285	100.4
69.99	14.72	99.9	0.300	4.65	21.40	1.11	1.404	100.5
70.04	14.73	99.9	0.400	5.68	26.34	1.05	1.517	100.5
69.96	14.68	100.0	0.600	7.57	34.59	1.61	1.735	100.3
70.01	14.70	100.3	0.800	9.04	41.16	1.94	1.944	100.1
70.20	14.71	100.4	1.000	10.21	46.43	2.21	2.154	99.9
70.27	14.71	100.4	1.200	11.17	50.93	2.55	2.356	99.7
90.06	14.69	100.3	0.100	2.17	6.72	0.78	1.487	100.4
90.09	14.66	100.1	0.201	2.84	12.51	0.96	1.605	100.5
90.00	14.68	99.9	0.300	3.62	17.41	1.04	1.720	100.6
89.93	14.69	99.9	0.401	4.45	21.82	1.17	1.839	100.5
90.14	14.68	99.8	0.601	5.98	29.07	1.49	2.069	100.4
90.03	14.65	99.9	0.800	7.35	35.04	1.76	2.284	100.2
90.02	14.67	100.0	1.000	8.50	40.14	2.03	2.492	100.0
90.29	14.66	100.1	1.201	9.45	44.38	2.26	2.705	99.7
89.92	14.70	100.1	1.400	10.31	48.15	2.56	2.907	99.5

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

100°F, Nominal 10 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.11	10.01	99.8	0.101	7.72	25.61	0.86	0.395	97.9
19.98	10.01	99.9	0.200	10.98	40.19	1.25	0.497	98.3
20.12	10.00	99.9	0.300	12.95	50.09	1.64	0.599	98.5
20.00	9.99	100.0	0.400	14.37	57.55	2.05	0.696	98.7
30.21	10.00	100.3	0.100	4.79	18.11	0.84	0.550	98.8
30.06	10.01	100.3	0.200	7.52	30.48	1.15	0.657	99.0
30.07	10.01	100.3	0.300	9.54	39.38	1.43	0.762	99.1
30.02	9.99	100.3	0.400	11.07	46.42	1.76	0.862	99.1
29.97	9.97	100.5	0.599	13.17	56.26	2.40	1.064	99.0
40.02	10.01	100.6	0.101	3.52	14.31	0.83	0.703	99.2
40.04	9.99	100.6	0.200	5.50	24.54	1.07	0.813	99.3
39.97	10.00	100.6	0.300	7.30	32.64	1.33	0.920	99.3
39.97	10.00	100.6	0.400	8.75	38.96	1.54	1.027	99.2
40.01	10.02	100.7	0.600	10.91	48.56	2.09	1.235	99.4
40.07	10.03	100.7	0.798	12.40	55.60	2.61	1.435	99.3
55.19	9.94	100.6	0.099	2.58	10.55	0.82	0.937	99.6
55.02	9.97	100.6	0.200	3.90	19.02	1.03	1.051	99.7
54.90	10.03	100.5	0.300	5.25	25.85	1.25	1.161	99.8
55.06	10.01	100.5	0.400	6.46	31.47	1.41	1.270	99.8
55.21	9.99	100.5	0.600	8.48	40.31	1.83	1.489	99.7
55.01	9.98	100.5	0.801	10.09	47.27	2.20	1.694	99.6
55.22	9.98	100.5	0.999	11.30	52.53	2.68	1.903	99.6
70.12	9.97	100.6	0.100	2.21	8.51	0.83	1.175	99.9
70.06	9.97	100.5	0.201	3.10	15.62	1.01	1.286	99.9
70.05	9.98	100.5	0.301	4.11	21.51	1.33	1.400	99.9
69.97	10.00	100.4	0.400	5.12	26.45	1.50	1.513	100.0
69.95	10.01	100.3	0.600	6.93	34.65	1.66	1.732	100.1
70.03	10.00	100.4	0.799	8.41	41.13	2.01	1.942	99.6
70.17	10.00	100.4	0.999	9.61	46.38	2.31	2.154	99.7
70.16	10.01	100.4	1.200	10.62	50.92	2.73	2.357	99.6
90.14	10.00	100.4	0.100	1.94	6.71	0.84	1.488	100.3
90.08	9.99	100.3	0.201	2.54	12.53	0.94	1.600	100.4
89.95	9.99	100.1	0.300	3.26	17.55	1.11	1.712	100.4
89.95	9.99	99.9	0.401	4.07	21.81	1.26	1.839	100.7
89.98	10.03	99.9	0.600	5.56	29.05	1.56	2.065	100.5
90.13	9.94	99.9	0.800	6.89	35.04	1.81	2.284	100.3
89.94	10.01	100.1	1.001	8.07	40.28	2.06	2.486	99.7
90.09	9.98	100.1	1.199	9.04	44.45	2.38	2.697	99.2
90.17	9.97	100.0	1.400	9.89	48.25	2.63	2.902	99.2

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

100°F, Nominal 5 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.11	5.00	100.5	0.101	5.58	25.47	1.04	0.396	98.2
19.99	4.99	100.5	0.200	8.95	40.27	1.50	0.497	98.2
20.05	5.00	100.5	0.300	11.15	50.13	2.00	0.598	98.3
19.99	4.99	100.6	0.400	12.73	57.43	2.49	0.697	98.2
29.94	5.00	100.5	0.099	3.53	18.21	0.96	0.545	98.2
30.04	5.02	100.6	0.200	5.98	30.47	1.30	0.655	98.3
29.86	5.00	100.6	0.300	8.02	39.62	1.66	0.758	98.1
29.94	4.99	100.6	0.400	9.59	46.46	1.98	0.862	98.2
30.05	5.01	100.6	0.600	11.85	56.35	2.71	1.065	98.2
40.15	4.93	100.6	0.099	2.64	14.23	0.91	0.696	98.2
40.01	4.95	100.6	0.199	4.42	24.75	1.17	0.805	98.2
39.91	4.98	100.6	0.300	6.11	32.88	1.46	0.911	98.2
39.96	5.00	100.4	0.401	7.55	39.22	1.75	1.021	98.3
40.10	4.99	100.4	0.600	9.77	48.80	2.32	1.230	98.4
39.88	5.00	100.3	0.801	11.42	55.93	2.91	1.431	98.2
55.01	4.97	100.4	0.100	2.10	10.84	0.88	0.924	98.6
55.02	4.96	100.3	0.200	3.24	19.30	1.08	1.036	98.6
55.16	4.96	100.2	0.300	4.47	26.13	1.31	1.149	98.8
55.16	5.03	100.2	0.400	5.64	31.69	1.51	1.261	98.9
54.88	4.97	100.1	0.599	7.69	40.75	1.96	1.469	98.9
55.10	4.96	100.2	0.800	9.28	47.51	2.42	1.684	98.9
55.00	4.99	100.3	1.000	10.54	52.97	2.88	1.888	98.7
70.07	5.01	100.2	0.100	1.85	8.66	0.88	1.156	99.2
69.91	4.98	100.2	0.200	2.65	15.76	1.04	1.266	99.2
69.96	5.00	100.1	0.300	3.59	21.72	1.27	1.379	99.3
70.06	5.03	100.0	0.400	4.55	26.78	1.27	1.494	99.4
70.04	4.98	99.9	0.600	6.31	34.97	1.73	1.716	99.5
69.89	5.00	99.9	0.800	7.82	41.56	2.11	1.926	99.2
70.29	5.00	100.0	1.000	9.02	46.68	2.40	2.143	99.1
70.28	5.01	100.0	1.200	10.04	51.10	2.88	2.349	98.9
89.93	4.93	99.7	0.100	1.65	6.91	0.87	1.448	100.0
89.89	4.97	99.5	0.199	2.25	12.73	1.03	1.568	100.1
89.92	5.01	99.3	0.301	2.95	17.79	1.16	1.691	100.2
90.07	5.00	99.3	0.400	3.70	22.14	1.27	1.806	100.1
89.90	4.96	99.3	0.600	5.19	29.51	1.61	2.033	100.0
90.04	5.03	99.3	0.800	6.51	35.49	1.92	2.255	100.0
90.15	4.98	99.6	1.000	7.68	40.47	2.18	2.472	99.6
90.01	4.99	99.7	1.200	8.67	44.86	2.50	2.674	99.2
90.12	5.01	99.7	1.401	9.51	48.63	2.71	2.881	98.8

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

100°F, Nominal 2 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.04	1.99	100.6	0.099	4.34	24.99	1.17	0.396	100.1
20.05	1.98	100.7	0.201	7.54	40.04	1.73	0.501	100.0
20.06	1.98	100.7	0.301	9.85	49.91	2.29	0.604	100.1
30.05	2.01	101.0	0.100	2.94	18.37	1.04	0.546	99.4
30.05	2.01	100.9	0.200	5.20	30.62	1.42	0.654	99.2
29.92	2.01	100.9	0.301	7.19	39.73	1.79	0.757	99.2
29.91	2.02	100.9	0.400	8.81	46.55	2.19	0.860	99.1
29.99	2.00	100.9	0.581	10.97	55.57	2.94	1.045	98.8
40.15	2.00	100.7	0.100	2.33	14.52	0.97	0.690	98.7
40.02	1.99	100.8	0.200	3.98	25.05	1.27	0.798	98.7
39.96	1.98	100.7	0.299	5.63	32.99	1.57	0.906	98.8
40.01	2.00	100.5	0.401	7.05	39.52	1.85	1.015	98.6
39.94	2.01	100.5	0.600	9.35	49.10	2.46	1.223	98.6
40.00	2.01	100.5	0.774	10.83	55.30	3.01	1.399	98.5
54.96	1.95	100.3	0.100	1.92	11.03	0.93	0.908	98.8
55.06	1.98	100.4	0.200	3.04	19.54	1.15	1.023	98.9
54.96	2.02	100.3	0.300	4.27	26.49	1.35	1.132	98.9
55.06	2.06	100.1	0.400	5.45	32.19	1.59	1.244	99.1
55.13	2.05	100.1	0.600	7.49	41.09	2.02	1.461	99.2
54.87	2.11	100.1	0.800	9.12	47.98	2.50	1.666	99.0
55.36	2.15	100.1	1.000	10.34	53.17	3.00	1.881	98.9
69.88	2.53	100.1	0.101	1.78	8.89	0.90	1.138	99.2
70.12	2.56	100.1	0.199	2.59	15.87	1.07	1.255	99.6
70.09	2.59	99.9	0.301	3.53	21.94	1.38	1.370	99.7
69.98	2.63	99.9	0.401	4.50	27.02	1.42	1.483	99.9
70.09	2.66	100.0	0.602	6.28	35.31	1.82	1.705	99.8
70.00	2.68	100.0	0.801	7.78	41.85	2.23	1.913	99.7
69.90	2.72	100.1	1.001	9.01	47.20	2.57	2.122	99.5
69.81	2.74	100.1	1.199	10.00	51.69	2.98	2.319	99.4
90.03	3.23	100.1	0.100	1.75	6.86	0.90	1.453	100.0
90.03	3.30	100.1	0.200	2.30	12.83	1.06	1.560	100.0
90.01	3.25	100.0	0.299	2.97	17.89	1.14	1.669	100.1
89.78	3.35	100.0	0.400	3.72	22.45	1.28	1.781	100.2
89.84	3.42	99.9	0.599	5.19	29.78	1.57	2.013	100.3
89.94	3.45	99.9	0.799	6.54	35.83	1.87	2.231	100.0
89.97	3.35	99.9	1.001	7.70	40.90	2.17	2.447	99.8
90.09	3.44	99.9	1.200	8.67	45.21	2.50	2.653	99.7
90.16	3.51	99.9	1.401	9.55	48.94	2.92	2.863	99.3

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

75°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.05	14.65	73.8	0.100	10.24	32.19	0.56	0.310	74.4
20.05	14.71	73.7	0.199	13.45	48.16	0.87	0.413	74.6
19.93	14.71	73.8	0.298	15.22	58.62	1.17	0.509	74.7
19.93	14.70	73.8	0.401	16.26	65.70	1.48	0.610	74.6
29.97	14.68	74.0	0.101	6.69	23.85	0.56	0.423	74.6
30.02	14.70	74.1	0.200	9.79	37.95	0.80	0.526	74.7
29.99	14.67	74.1	0.300	11.85	47.73	1.04	0.629	74.6
30.07	14.65	74.2	0.400	13.23	54.87	1.29	0.729	74.5
29.89	14.63	74.2	0.601	15.13	64.63	1.78	0.931	74.1
39.97	14.64	74.2	0.101	4.73	19.09	0.55	0.527	74.3
39.94	14.67	74.1	0.199	7.39	31.32	0.73	0.636	74.6
39.89	14.65	74.1	0.300	9.40	40.36	0.95	0.743	74.5
39.94	14.67	74.1	0.401	10.90	47.18	1.15	0.849	74.6
40.03	14.64	74.1	0.601	12.98	56.88	1.58	1.056	74.3
39.90	14.64	74.1	0.800	14.38	63.90	1.98	1.252	73.8
55.01	14.70	73.9	0.099	3.15	14.37	0.54	0.691	74.6
54.89	14.68	73.8	0.200	5.13	24.85	0.69	0.806	74.9
54.99	14.65	73.8	0.299	6.84	32.60	0.87	0.918	74.9
55.04	14.67	73.8	0.400	8.30	39.04	1.01	1.025	74.3
55.11	14.67	73.9	0.600	10.41	48.15	1.36	1.246	75.6
55.07	14.64	74.0	0.800	11.96	55.07	1.73	1.453	75.3
55.19	14.66	73.9	1.002	13.23	60.83	2.07	1.647	73.7
70.03	14.65	74.0	0.101	2.41	11.60	0.53	0.868	75.7
69.95	14.66	74.0	0.199	3.82	20.28	0.66	0.982	75.1
69.92	14.69	73.9	0.299	5.17	27.39	0.81	1.092	75.4
69.99	14.68	73.9	0.400	6.42	33.30	0.96	1.201	75.1
70.08	14.67	74.0	0.500	7.55	38.19	1.11	1.308	74.8
69.90	14.71	74.0	0.601	8.53	42.55	1.23	1.412	74.5
69.99	14.69	74.0	0.799	10.05	48.96	1.54	1.633	75.0
69.93	14.68	73.9	0.999	11.27	54.25	1.83	1.841	75.2
70.22	14.66	74.2	1.203	12.34	59.03	2.06	2.038	73.9
89.95	14.64	73.7	0.099	1.90	9.19	0.55	1.081	75.2
90.00	14.65	73.7	0.200	2.88	16.68	0.64	1.201	75.0
89.94	14.65	73.8	0.301	3.96	22.74	0.78	1.321	74.9
90.04	14.68	73.8	0.400	4.95	27.78	0.89	1.439	75.6
90.03	14.63	73.9	0.499	5.88	32.32	1.02	1.544	75.4
89.83	14.69	73.9	0.599	6.76	36.23	1.10	1.653	75.1
90.03	14.69	74.0	0.801	8.19	42.64	1.38	1.878	75.4
90.07	14.71	73.9	1.002	9.50	47.99	1.60	2.087	74.8
89.96	14.70	73.8	1.200	10.56	52.47	1.80	2.287	74.3
89.88	14.71	73.8	1.399	11.40	56.03	2.10	2.498	74.5

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

50°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.98	14.65	49.0	0.102	11.35	39.71	0.46	0.257	50.9
20.00	14.63	49.3	0.198	14.45	55.84	0.73	0.355	50.7
20.05	14.65	49.6	0.299	16.05	65.73	1.00	0.455	50.9
20.02	14.68	49.7	0.400	17.05	72.13	1.29	0.555	50.7
19.96	14.67	49.9	0.601	18.21	80.04	1.88	0.751	50.5
29.92	14.67	48.6	0.100	7.58	30.13	0.43	0.333	50.9
29.99	14.67	48.6	0.199	11.02	45.60	0.64	0.436	50.5
29.98	14.67	48.7	0.300	13.07	55.55	0.85	0.539	50.4
29.94	14.65	48.5	0.400	14.44	62.77	1.07	0.638	50.6
30.00	14.66	48.8	0.401	14.43	62.49	1.09	0.641	50.2
29.86	14.66	48.5	0.599	16.18	71.35	1.54	0.839	50.1
40.01	14.67	48.2	0.099	5.32	24.05	0.41	0.411	50.5
39.95	14.66	48.4	0.200	8.47	38.35	0.59	0.521	50.6
39.95	14.66	48.3	0.300	10.68	47.94	0.78	0.626	50.5
39.95	14.66	48.4	0.601	14.26	64.49	1.34	0.931	49.8
39.92	14.69	48.1	0.801	15.62	70.44	1.74	1.137	50.4
54.89	14.68	48.1	0.102	3.42	19.07	0.39	0.533	51.1
54.99	14.65	48.2	0.199	5.91	30.97	0.53	0.641	50.7
54.94	14.63	48.2	0.300	7.99	39.82	0.70	0.754	50.2
54.97	14.67	48.2	0.401	9.54	46.44	0.82	0.863	50.8
54.98	14.67	48.1	0.600	11.81	56.10	1.13	1.070	50.4
55.11	14.67	48.2	0.800	13.36	62.85	1.44	1.272	49.7
69.96	14.65	47.7	0.100	2.51	15.28	0.36	0.656	50.6
69.83	14.65	47.8	0.200	4.39	25.94	0.51	0.769	50.6
70.02	14.66	47.9	0.300	6.13	34.08	0.63	0.880	50.3
70.02	14.66	47.9	0.400	7.59	40.46	0.74	0.990	50.2
69.99	14.69	47.9	0.600	9.88	49.82	1.00	1.204	50.1
69.93	14.68	47.6	0.801	11.55	56.66	1.27	1.415	50.0
70.17	14.64	48.0	1.003	12.76	61.44	1.55	1.632	50.3
69.87	14.60	47.7	1.198	13.72	65.92	1.78	1.817	50.0
89.93	14.72	48.5	0.100	1.86	12.29	0.36	0.812	50.2
90.06	14.66	48.6	0.199	3.14	21.32	0.49	0.932	50.1
90.04	14.68	48.6	0.300	4.51	28.38	0.59	1.056	50.3
89.95	14.64	47.2	0.399	5.79	34.15	0.66	1.169	50.7
89.86	14.66	47.1	0.601	7.91	43.32	0.91	1.387	50.7
90.05	14.67	47.0	0.800	9.51	49.95	1.11	1.601	50.6
90.13	14.66	47.3	1.000	10.86	55.41	1.30	1.805	49.7
90.15	14.64	47.6	1.200	11.89	59.54	1.58	2.016	50.1
89.99	14.67	47.4	1.401	12.74	62.92	1.82	2.226	50.5

A/C TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

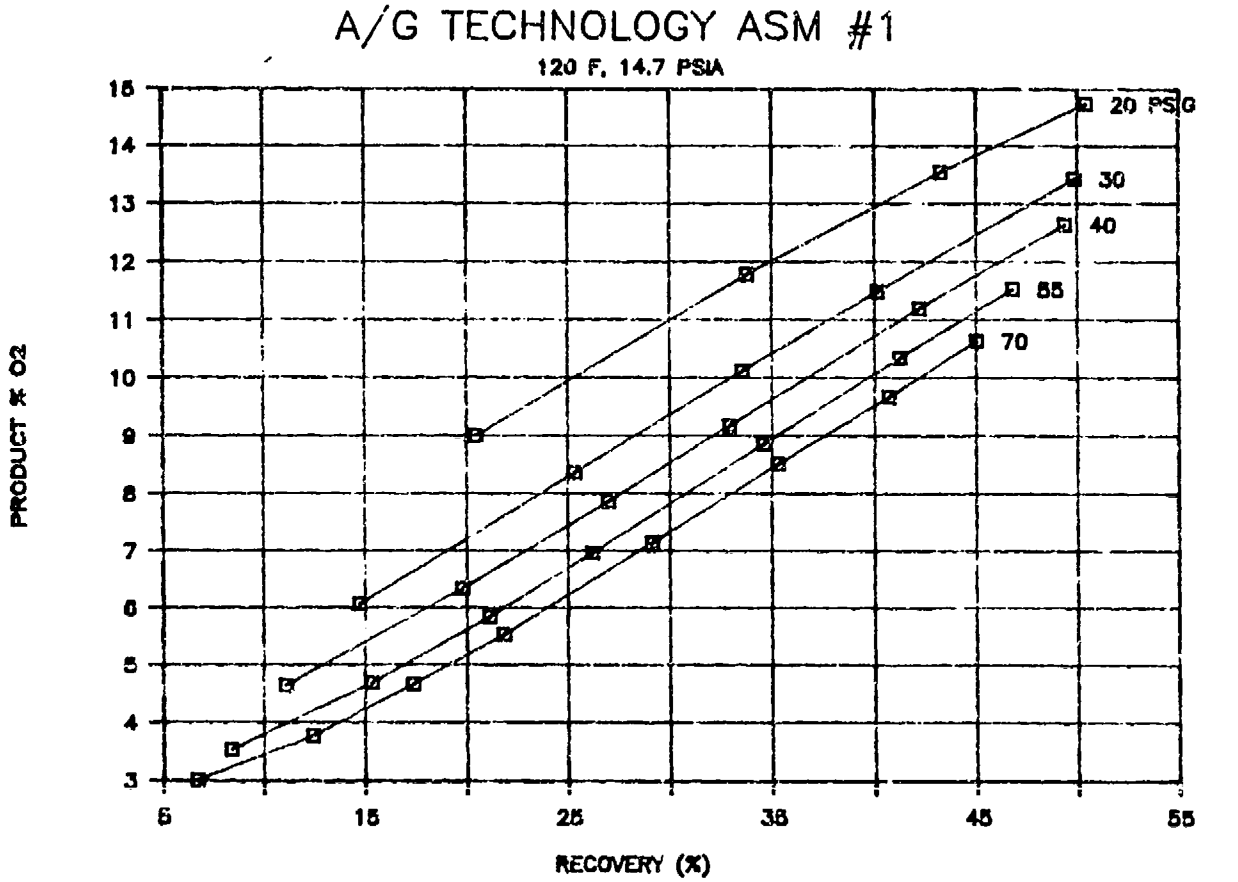
50°F, Nominal 5 PSIA

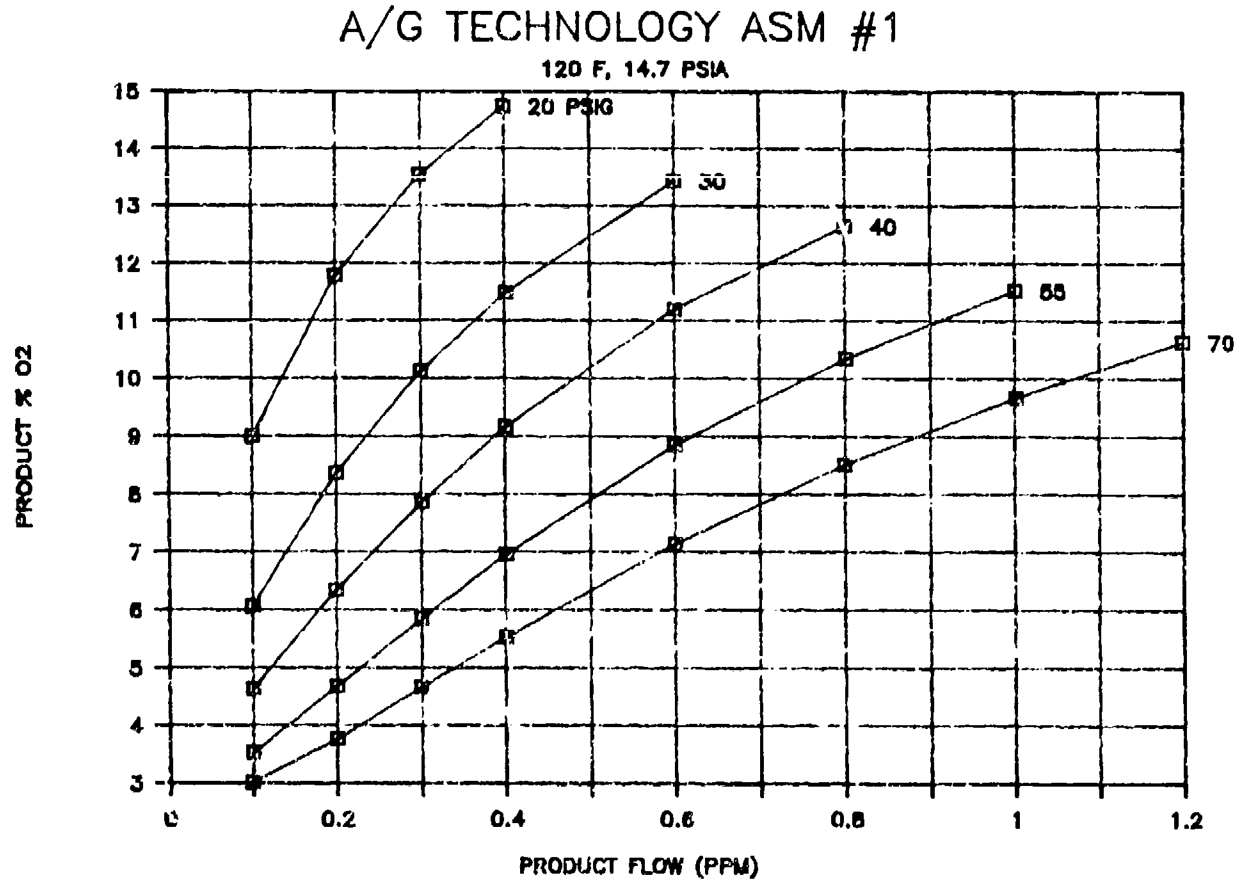
PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.94	5.00	48.8	0.099	7.43	38.94	0.63	0.255	51.0
19.97	4.97	47.7	0.199	11.26	55.59	1.02	0.359	50.2
19.90	4.98	48.2	0.299	13.51	65.04	1.41	0.459	52.0
20.11	4.97	49.8	0.399	14.75	71.18	1.80	0.560	50.8
30.05	4.99	47.6	0.099	4.42	29.06	0.55	0.341	51.2
30.05	4.99	47.5	0.200	7.87	44.51	0.83	0.450	51.2
29.98	4.99	47.5	0.299	10.19	54.25	1.13	0.552	50.9
29.97	5.00	47.5	0.400	11.88	61.50	1.40	0.651	50.8
29.97	5.00	47.6	0.600	14.06	70.53	1.99	0.851	50.6
39.96	4.96	47.7	0.101	3.04	24.36	0.50	0.417	51.1
39.94	4.99	47.7	0.200	5.84	37.87	0.73	0.527	50.8
40.03	4.96	47.8	0.300	8.01	47.16	0.95	0.636	50.4
39.95	4.97	47.7	0.399	9.68	54.07	1.16	0.739	50.1
39.94	4.99	47.8	0.600	12.07	63.48	1.63	0.946	50.0
39.90	5.03	47.7	0.801	13.62	69.63	2.15	1.150	50.1
54.98	4.97	47.6	0.100	2.05	18.67	0.47	0.536	51.0
54.97	4.99	47.7	0.199	4.01	30.68	0.62	0.650	50.8
55.11	4.98	47.7	0.299	5.82	39.35	0.80	0.760	50.5
55.03	5.00	47.6	0.400	7.36	45.95	0.96	0.870	50.4
55.04	4.99	47.7	0.600	9.75	55.46	1.35	1.082	50.4
54.93	5.03	47.4	0.801	11.51	62.03	1.70	1.291	50.7
55.08	5.01	47.4	0.998	12.81	66.97	2.08	1.490	49.8
70.02	4.97	47.4	0.100	1.55	15.25	0.47	0.656	51.0
69.98	4.95	47.5	0.200	3.00	25.97	0.57	0.772	50.8
69.90	4.96	47.5	0.300	4.51	33.94	0.69	0.885	50.7
70.03	4.96	47.5	0.401	5.87	40.22	0.86	0.996	50.5
69.93	5.00	47.5	0.599	8.13	49.46	1.14	1.212	50.5
70.01	4.98	47.0	0.800	9.75	56.45	1.44	1.417	50.7
70.11	4.95	47.0	1.001	11.07	61.32	1.75	1.633	50.1
70.17	4.96	47.1	1.199	12.14	65.56	2.04	1.828	49.1
89.85	4.99	47.2	0.099	1.22	12.24	0.41	0.807	50.8
89.99	4.98	47.3	0.201	2.25	21.56	0.53	0.931	50.3
89.85	4.98	47.3	0.301	3.38	28.80	0.64	1.044	50.2
89.97	5.00	47.4	0.399	4.50	34.12	0.77	1.169	50.9
89.91	4.99	47.4	0.600	6.52	43.39	0.97	1.383	50.4
89.95	4.95	47.0	0.797	8.07	50.22	1.24	1.588	50.2
89.96	5.00	47.3	1.002	9.45	55.44	1.46	1.808	49.5
90.04	5.00	46.9	1.201	10.54	59.60	1.72	2.016	49.3
89.87	5.03	46.9	1.399	11.41	62.89	1.97	2.224	49.8

APPENDIX D

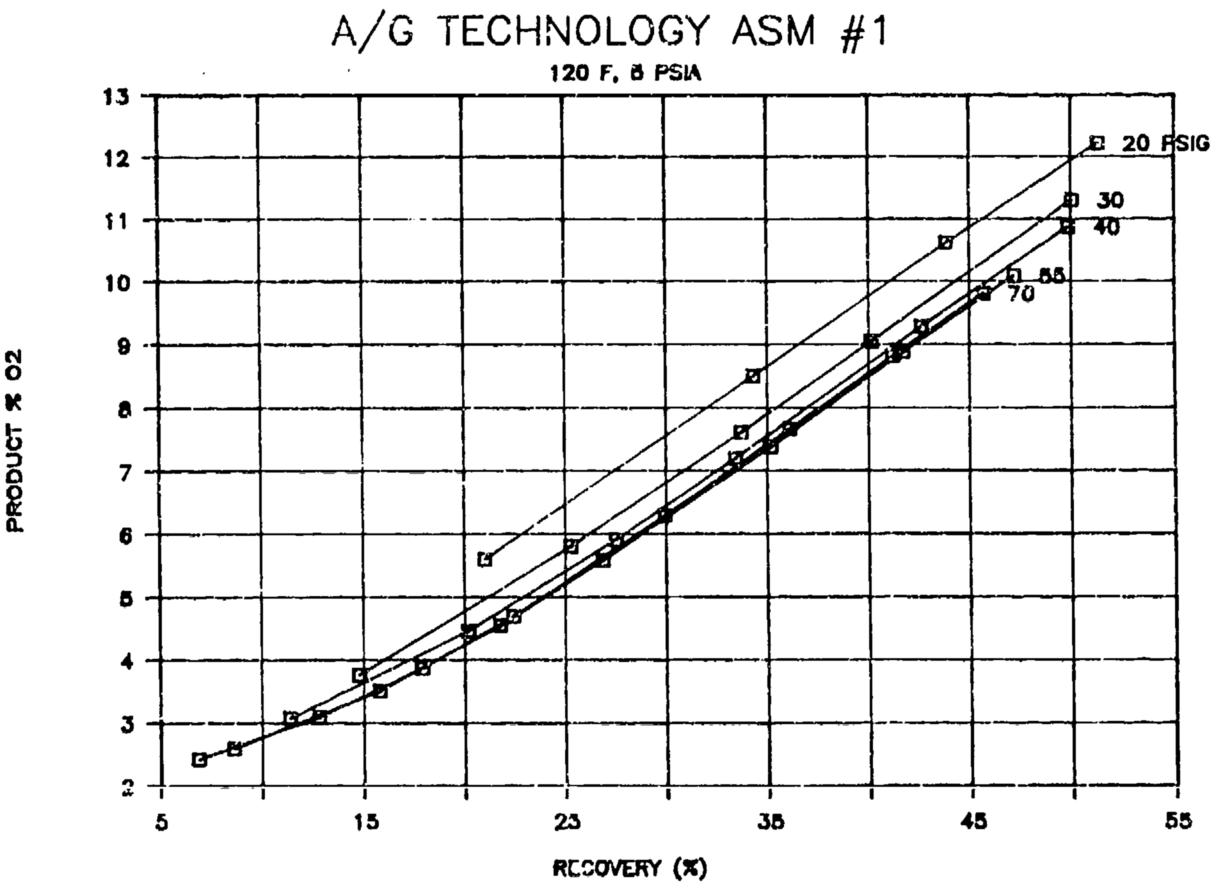
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA

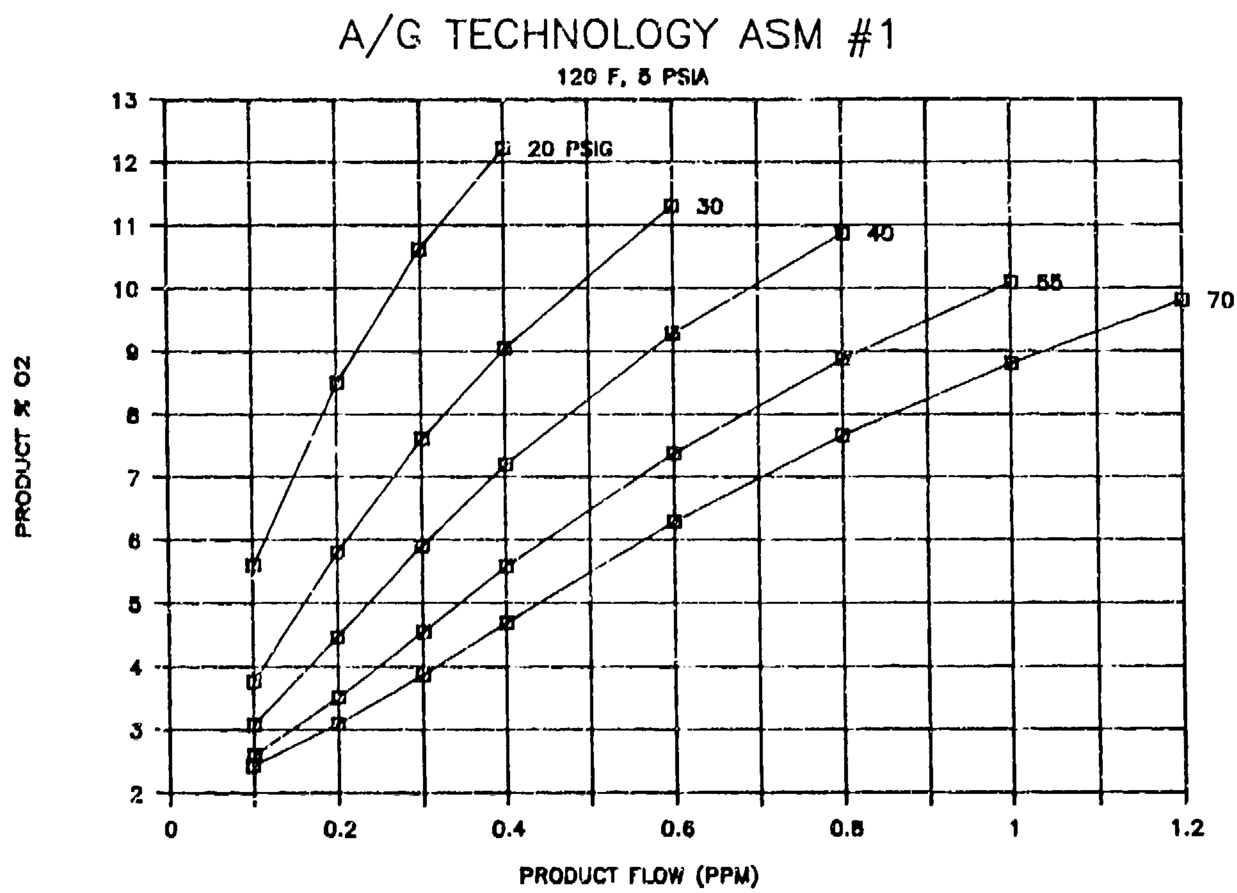
ASM #1 (S/N 6A-G/I300501AL)

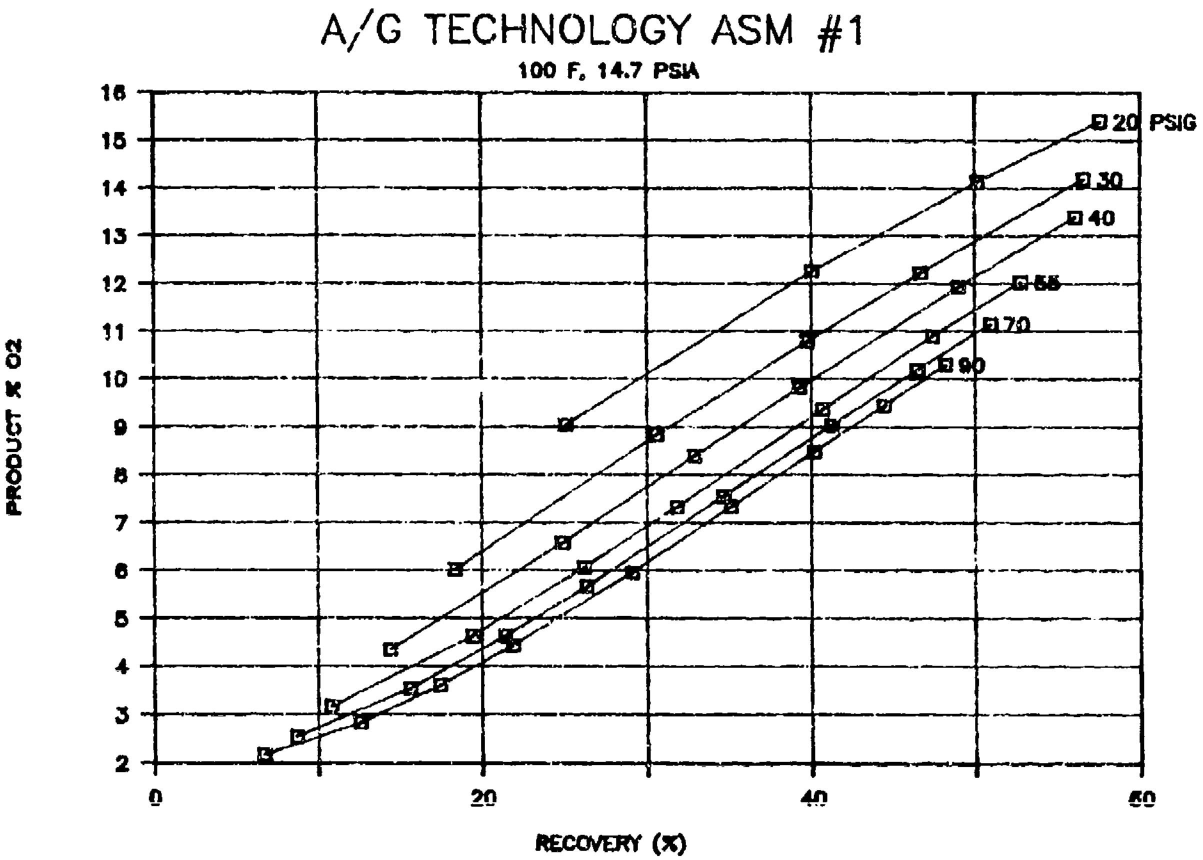


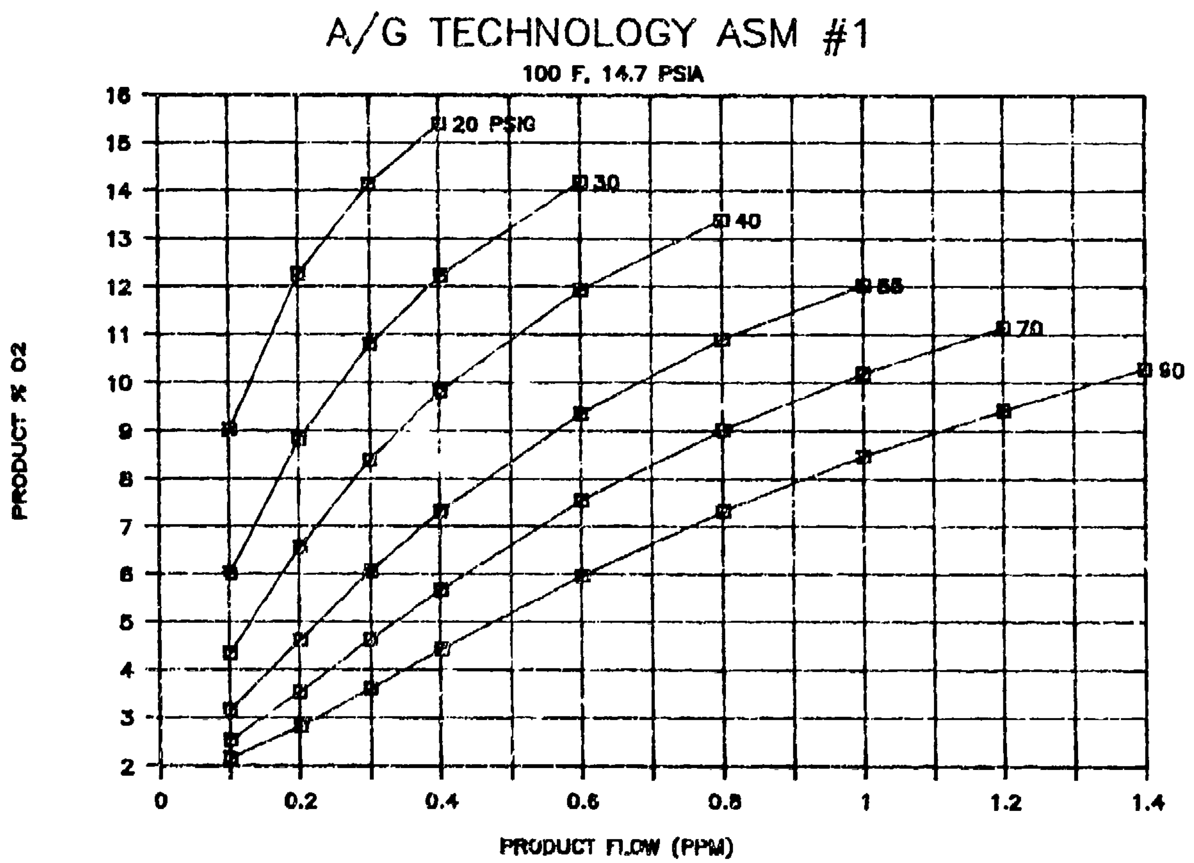


APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)

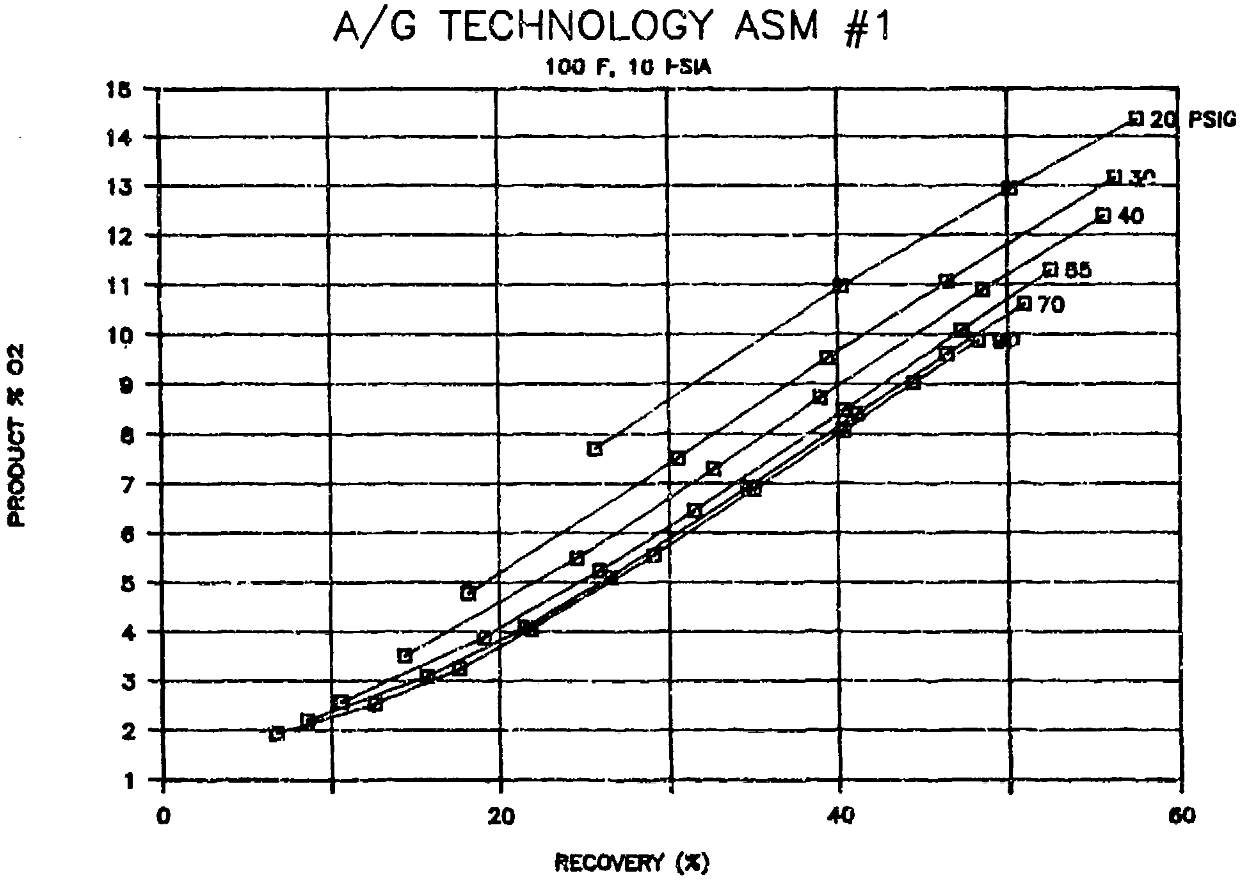


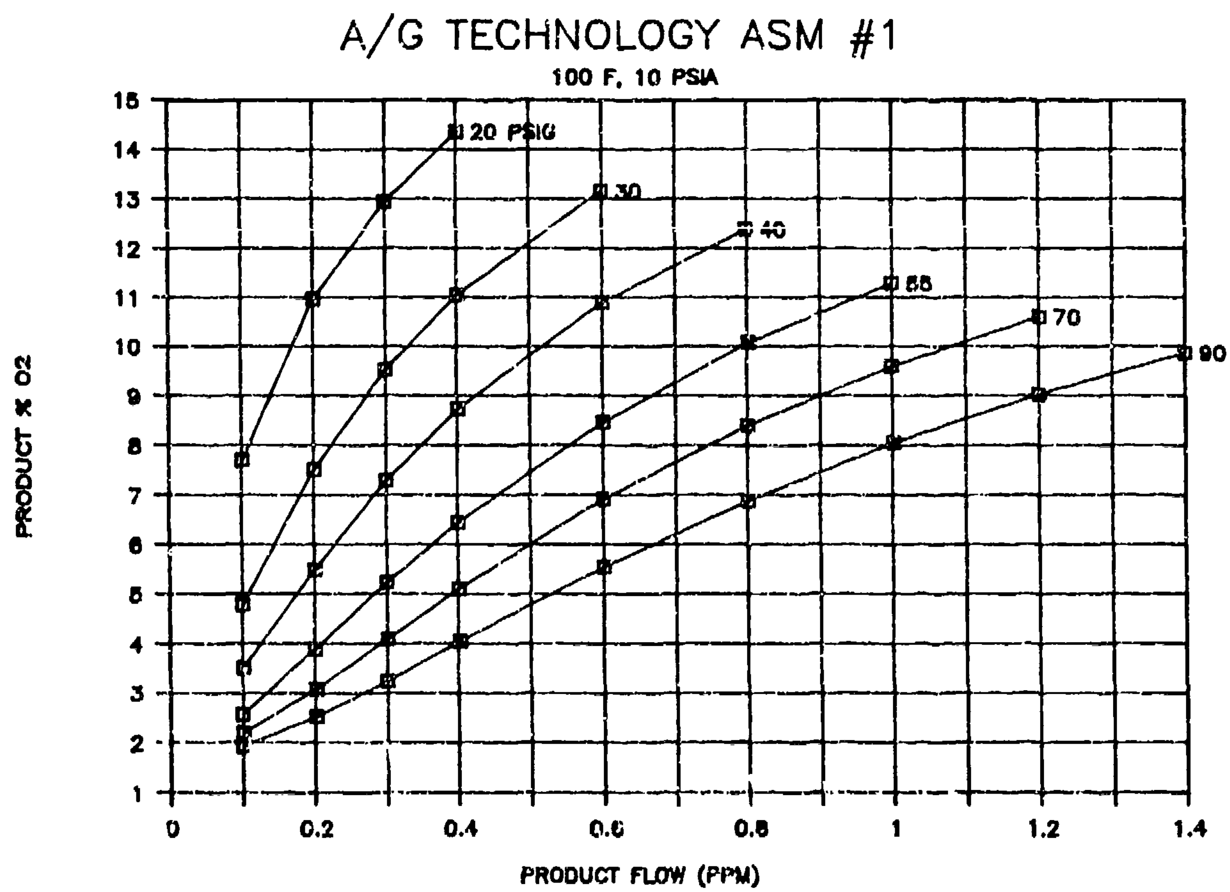



A/G TECHNOLOGY ASM #1
100 F, 14.7 PSIA
PRODUCT % O2
RECOVERY (%)
20 PSIG
30
40
55
70
90
0
20
40
60
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

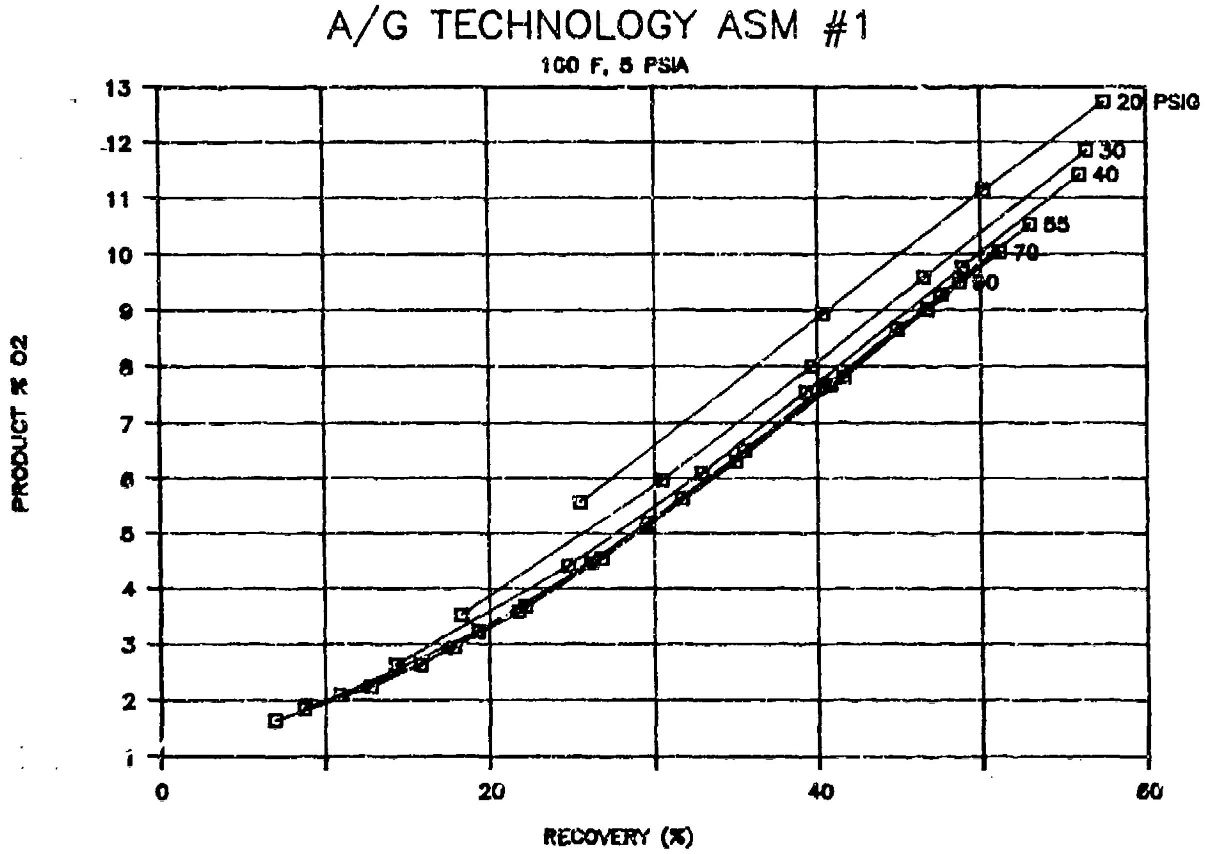

A/G TECHNOLOGY ASM #1
100 F, 14.7 PSIA
PRODUCT % O2
PRODUCT FLOW (PPM)
20 PSIG
30
40
55
70
90
0
0.2
0.4
0.6
0.8
1
1.2
1.4
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

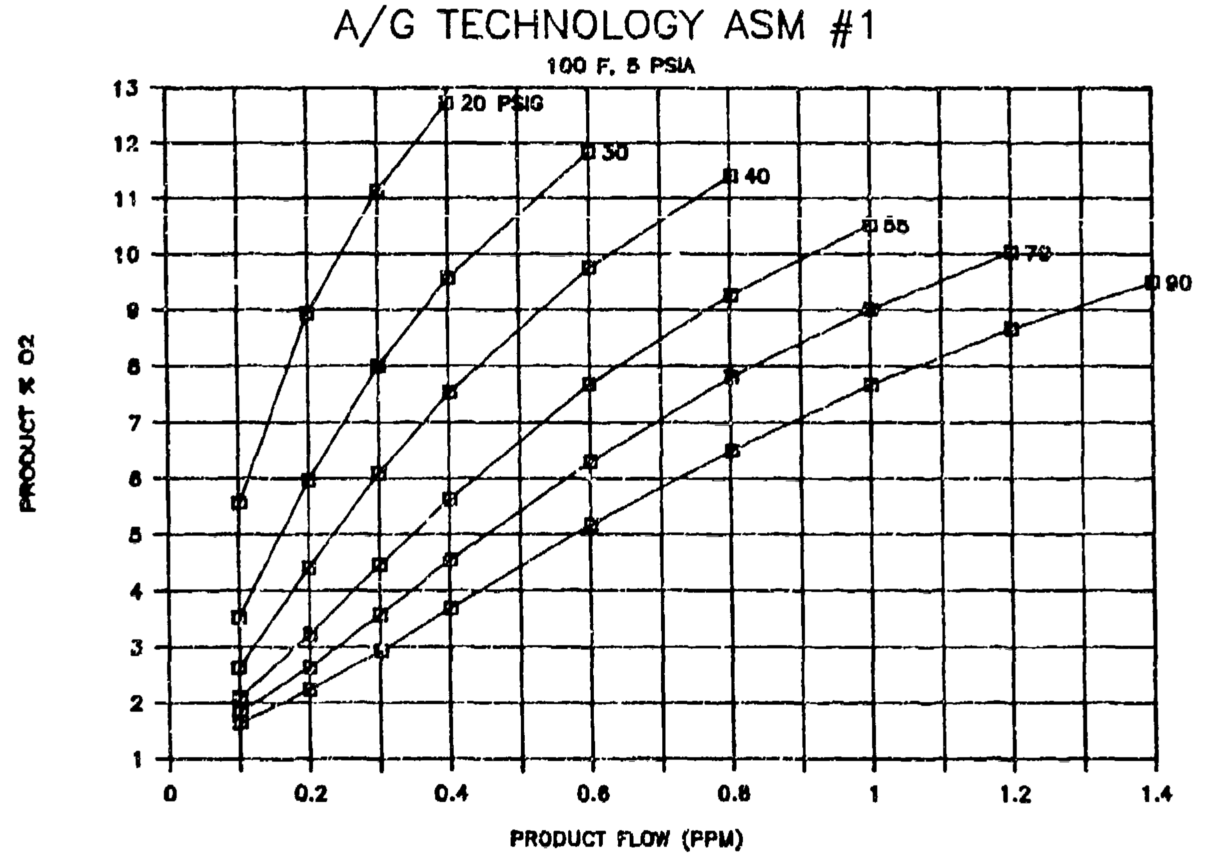
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)



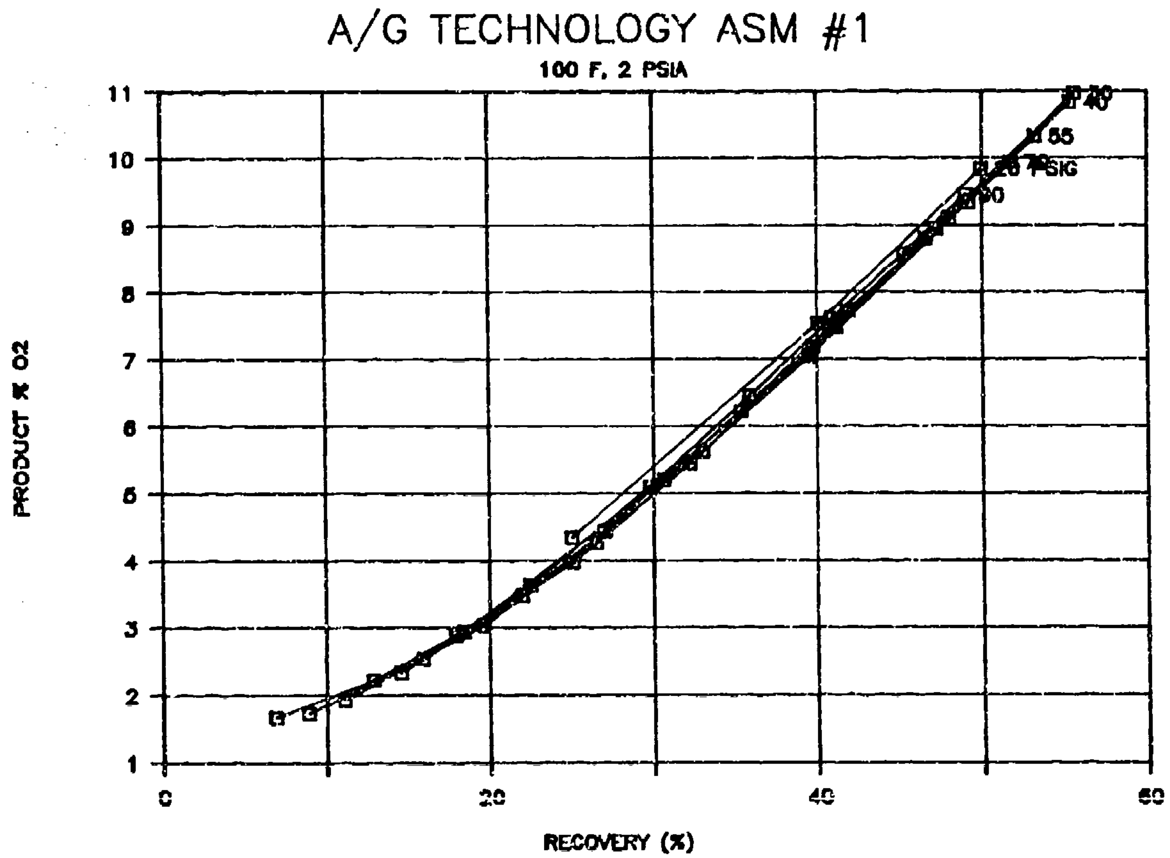


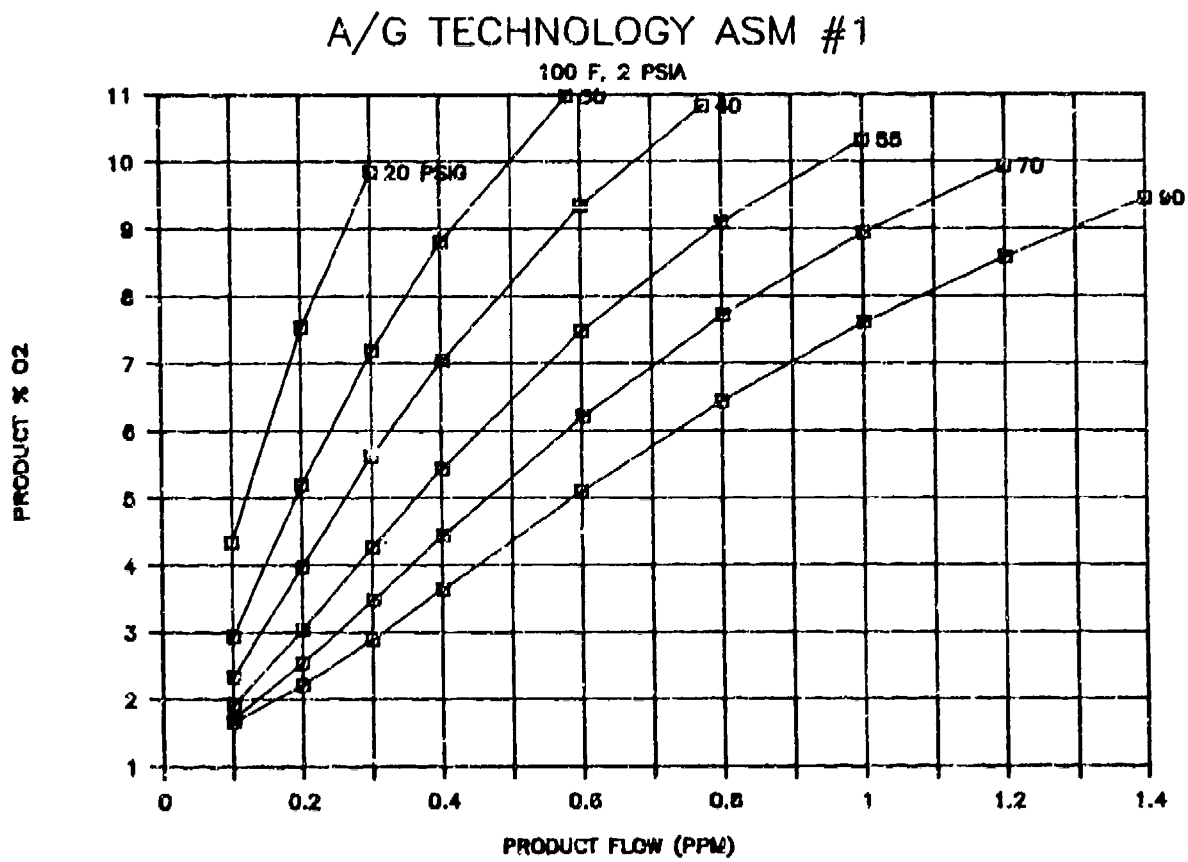
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)



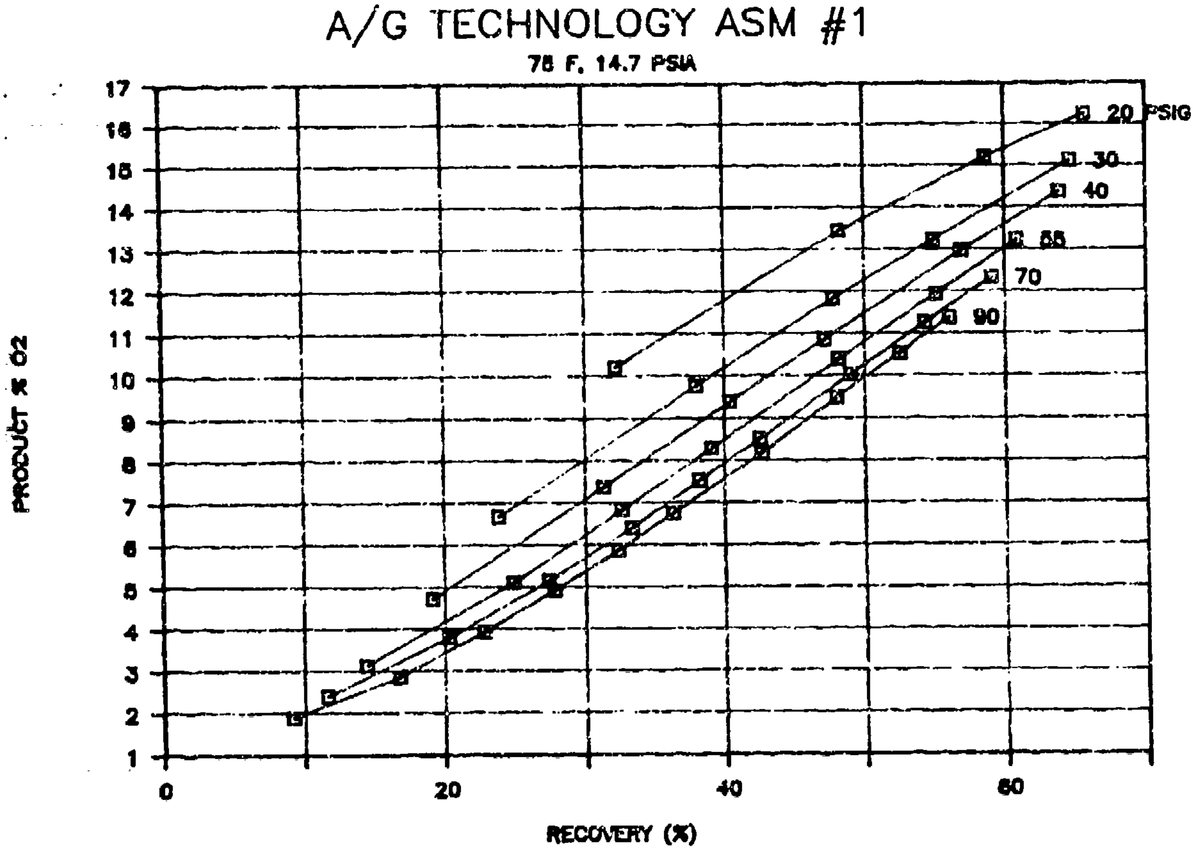


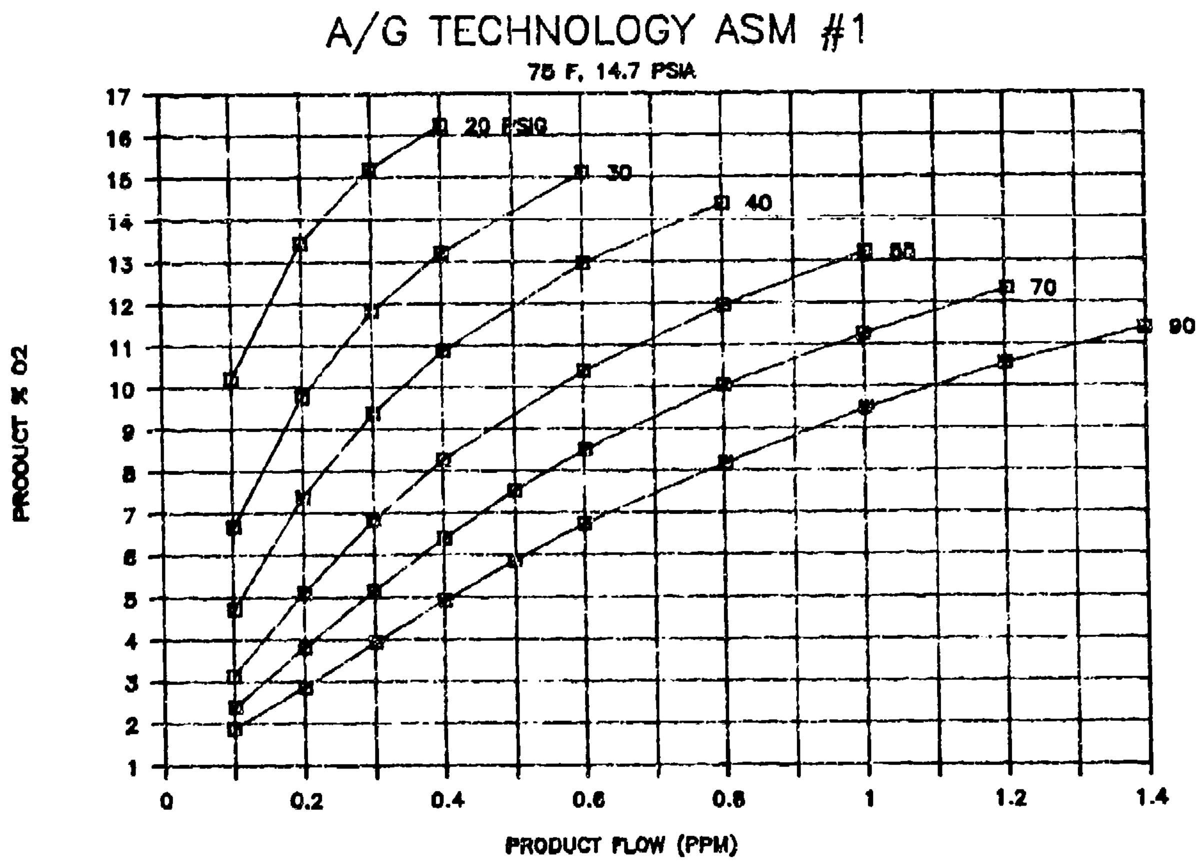
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)



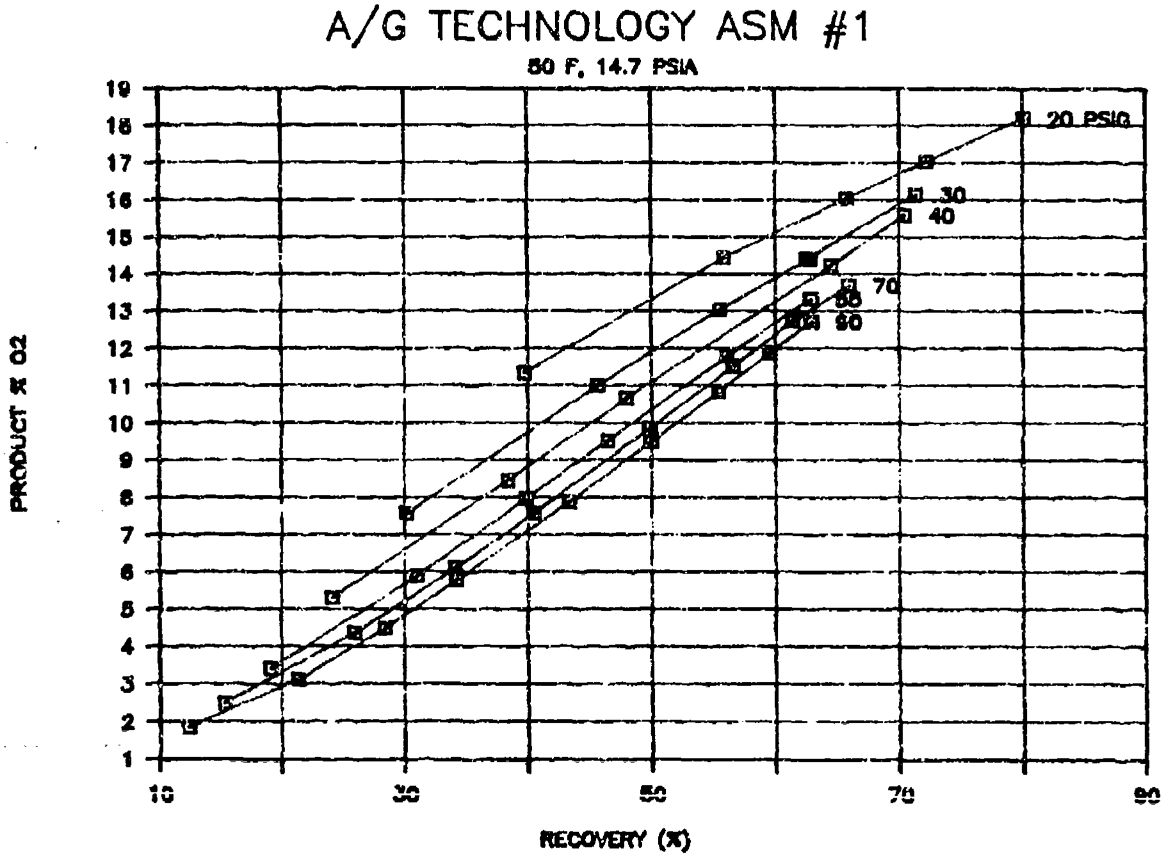


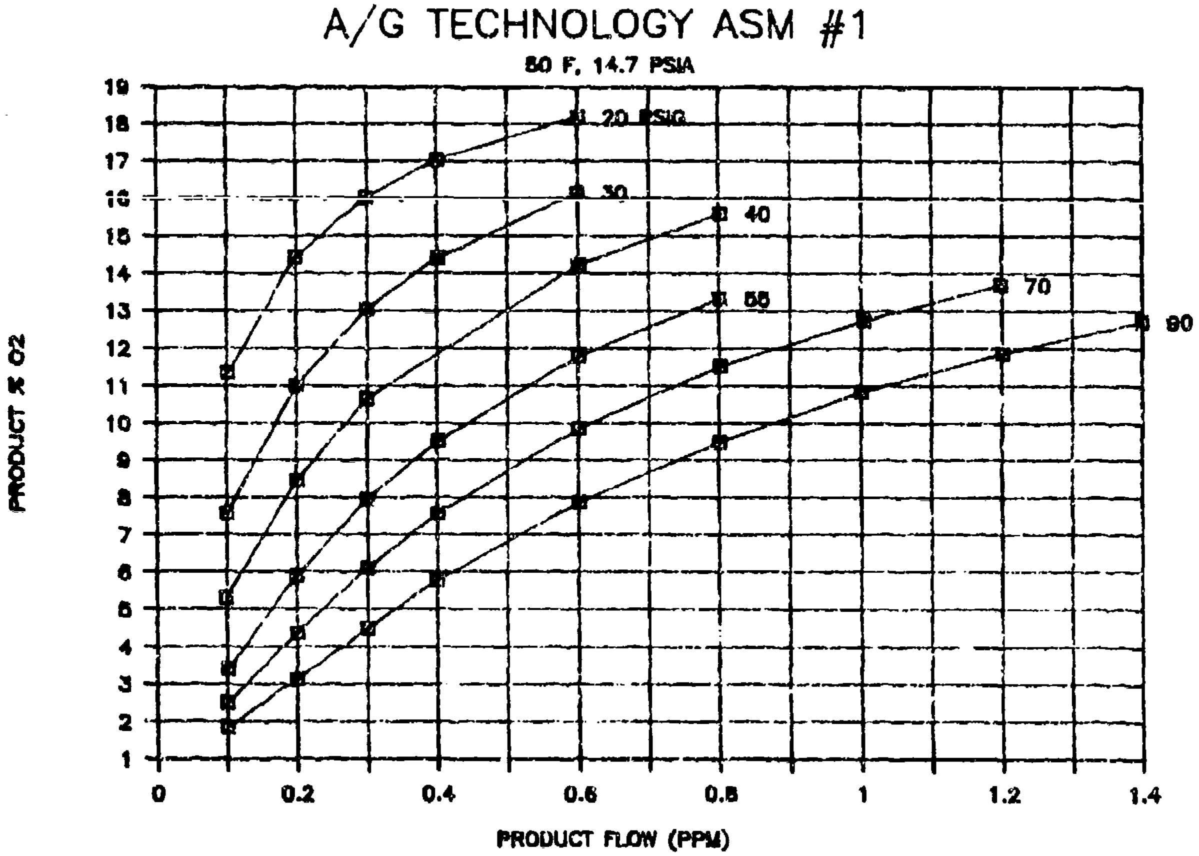
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)



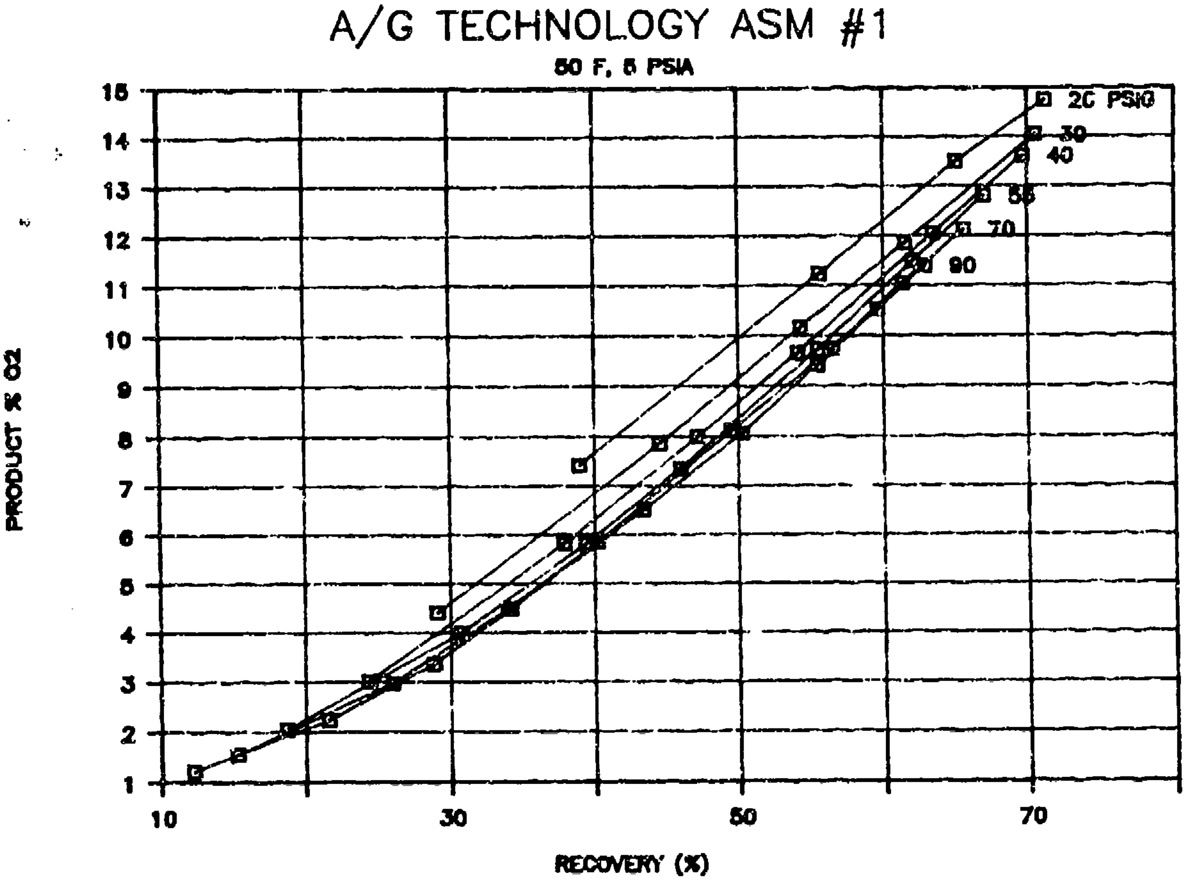


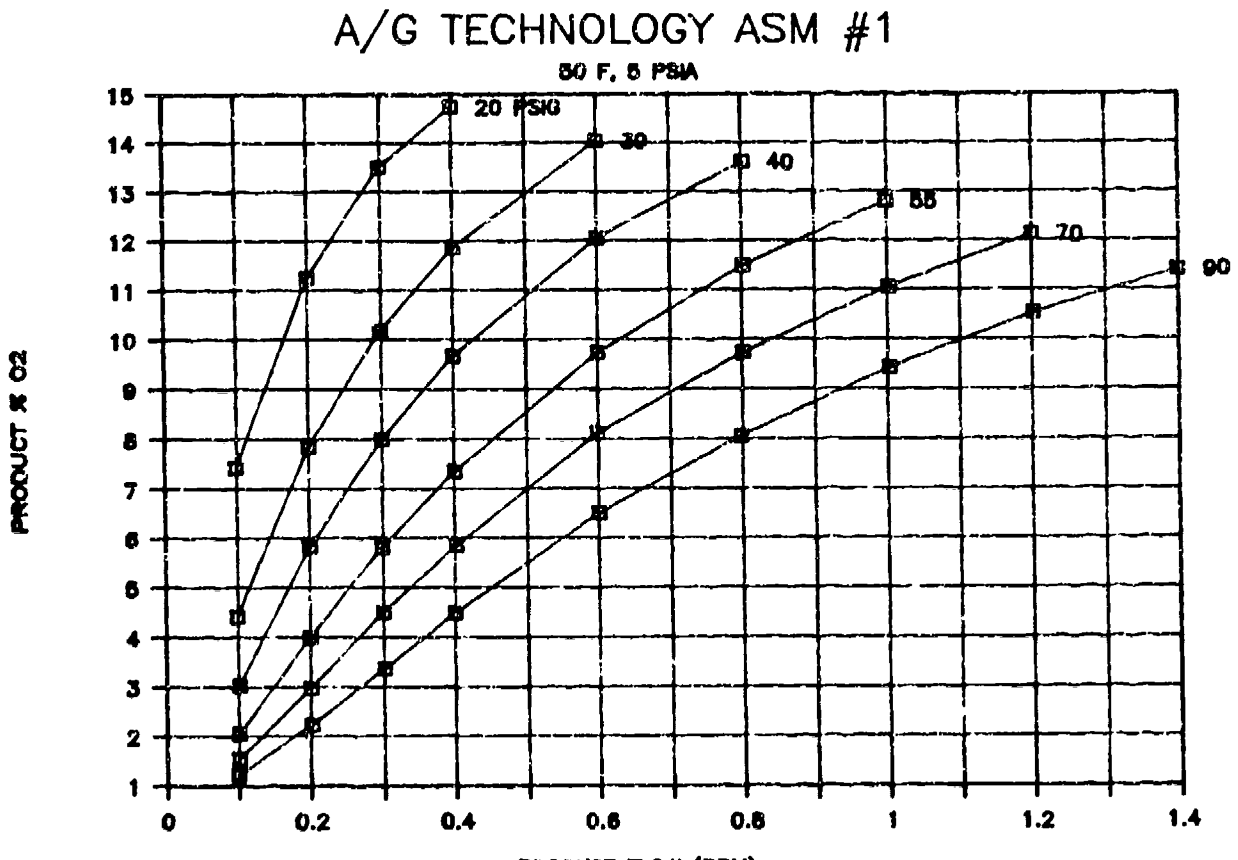
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)





APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #1 (S/N 6A-G/I300501AL)





APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

140°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.01	14.69	140.7	0.100	8.45	18.18	1.25	0.548	140.4
20.07	14.70	140.6	0.201	11.46	30.89	1.67	0.649	140.6
29.91	14.67	140.7	0.400	11.36	36.87	2.35	1.086	140.2
30.00	14.65	140.7	0.100	5.23	12.86	1.33	0.781	140.3
39.98	14.63	140.2	0.103	3.58	10.14	1.36	1.014	142.2
39.89	14.65	140.2	0.300	7.68	24.43	1.98	1.229	142.4
40.03	14.65	140.6	0.600	11.09	39.03	2.82	1.537	140.7
54.94	14.71	140.4	0.799	10.28	38.28	3.10	2.086	139.7
55.04	14.67	140.3	0.400	6.80	23.88	2.09	1.677	140.0
55.09	14.69	140.3	0.100	2.33	7.38	1.42	1.355	140.7

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

140°F, Nominal 5 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.08	5.00	140.5	0.201	8.60	31.63	2.29	0.634	140.3
20.02	5.00	140.5	0.101	5.36	18.95	1.69	0.532	140.1
29.95	5.08	140.5	0.101	3.27	13.33	1.65	0.756	140.1
29.89	5.01	140.6	0.400	9.35	37.66	2.97	1.061	139.5
39.90	5.02	140.6	0.600	9.67	40.31	3.34	1.488	138.3
40.04	5.01	140.5	0.301	6.05	25.51	2.29	1.179	137.9
40.11	4.95	140.5	0.101	2.29	10.44	1.59	0.964	137.8
54.88	5.07	139.6	0.102	1.64	7.99	1.54	1.279	138.4
54.84	5.05	139.5	0.399	5.76	24.88	2.35	1.605	137.9
55.08	5.01	139.6	0.798	9.29	39.61	3.41	2.013	137.0

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

120°F, Nominal 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.14	14.71	120.4	0.100	8.74	21.18	1.03	0.471	120.2
20.04	14.67	120.5	0.200	11.88	35.06	1.43	0.569	120.6
30.16	14.71	120.5	0.100	5.34	15.07	1.08	0.661	120.9
29.99	14.68	120.6	0.401	11.75	41.27	2.01	0.971	121.0
39.99	14.70	120.7	0.599	11.53	43.96	2.42	1.363	120.3
40.15	14.67	120.7	0.300	7.96	28.28	1.61	1.062	120.3
39.86	14.70	120.6	0.101	3.63	11.94	1.09	0.842	120.7
55.15	14.71	120.6	0.102	2.28	8.97	1.17	1.136	121.5
55.00	14.73	120.5	0.401	7.07	27.42	1.77	1.464	121.4
55.01	14.71	120.6	0.799	10.65	42.66	2.69	1.873	120.5
70.10	14.73	120.5	1.196	11.15	46.77	3.15	2.558	118.8
70.00	14.69	120.4	0.601	7.51	31.03	2.05	1.938	119.0
70.03	14.67	120.2	0.200	3.06	13.24	1.32	1.508	120.2

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

$120^{o}F$, Nominal 5 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (^{o}F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (^{o}F)
20.11	4.98	120.4	0.200	8.85	35.75	1.96	0.559	119.9
20.05	4.98	120.4	0.101	5.44	22.00	1.40	0.458	119.8
30.12	4.87	120.4	0.100	3.21	15.78	1.32	0.636	120.0
30.05	5.00	120.3	0.400	9.60	42.07	2.55	0.951	120.1
40.16	4.92	120.6	0.600	9.84	44.70	2.91	1.343	119.2
39.97	4.97	120.5	0.299	6.12	28.99	1.92	1.032	119.3
40.08	5.00	120.4	0.100	2.18	12.26	1.27	0.817	119.5
55.01	4.96	120.2	0.100	1.49	9.10	1.27	1.101	122.6
55.08	4.96	120.4	0.400	5.76	27.83	2.04	1.437	121.8
54.96	4.95	120.6	0.800	9.44	43.43	3.08	1.841	120.3
69.91	4.96	120.2	1.203	10.37	47.74	3.61	2.519	119.1
69.87	4.94	120.1	0.599	6.55	31.45	2.27	1.905	120.2
70.01	4.93	120.1	0.200	2.35	13.46	1.46	1.483	122.3

APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

100°F, Nominal 14.7 PSIA

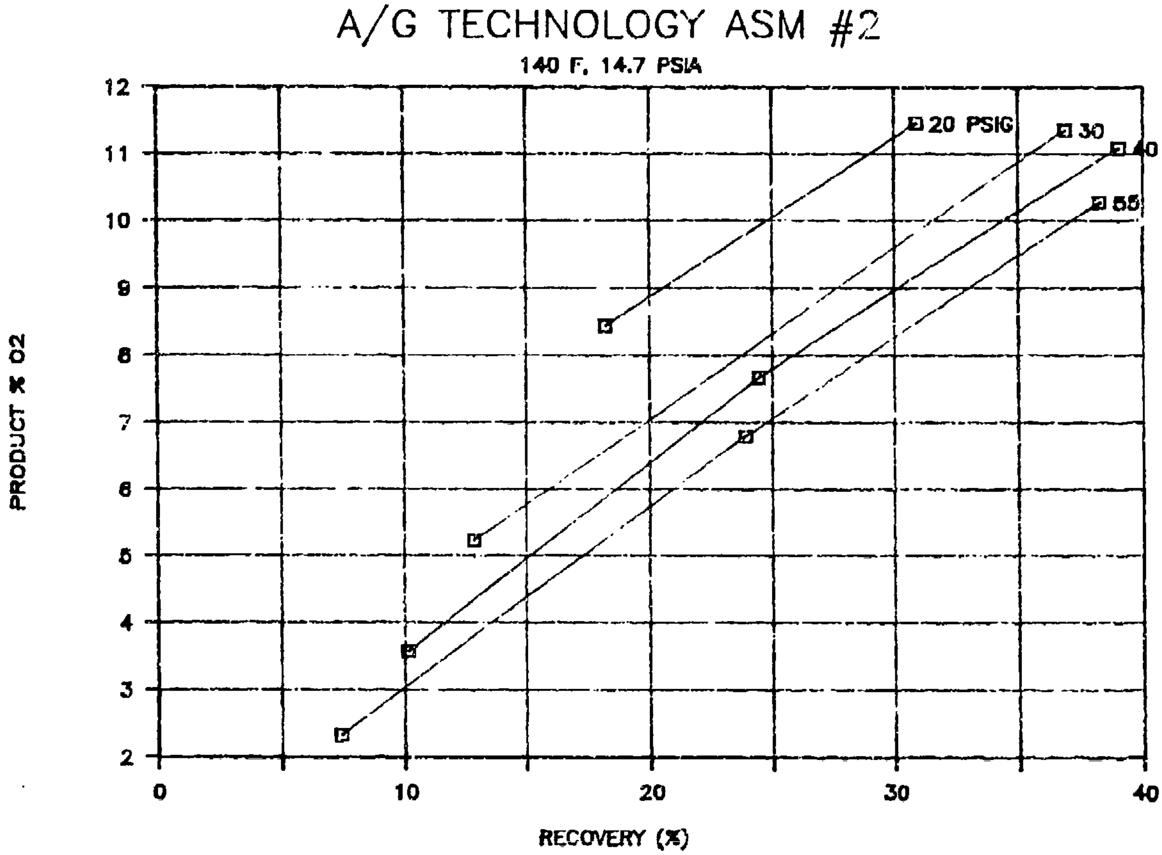
PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.98	14.67	100.4	0.101	9.31	25.49	0.86	0.395	101.1
19.85	14.67	100.4	0.200	12.54	40.63	1.22	0.493	101.1
30.10	14.71	100.4	0.400	12.34	46.66	1.74	0.857	101.0
30.06	14.75	100.5	0.100	5.72	18.35	0.86	0.547	101.2
39.87	14.75	99.9	0.100	3.76	14.56	0.84	0.687	101.3
39.93	14.76	99.9	0.300	8.49	32.94	1.35	0.910	101.6
39.95	14.75	100.1	0.599	12.11	49.04	2.13	1.222	101.2
54.97	14.69	99.8	0.800	11.21	48.43	2.25	1.652	99.1
55.04	14.68	99.8	0.399	7.45	32.07	1.45	1.244	100.0
54.91	14.68	99.8	0.101	2.28	11.02	0.85	0.918	100.7
69.96	14.73	99.3	0.202	3.13	15.97	1.04	1.267	101.9
70.01	14.75	99.7	0.601	7.84	35.15	1.68	1.711	101.1
69.99	14.70	100.1	1.201	11.68	52.12	2.74	2.304	98.7
90.02	14.71	99.5	1.606	11.63	53.19	3.03	3.020	97.1
89.87	14.67	99.1	0.602	6.30	30.37	1.52	1.982	98.9
89.99	14.68	99.0	0.802	7.77	36.35	1.85	2.205	99.2
89.94	14.67	99.1	0.201	2.23	12.94	1.01	1.550	100.3

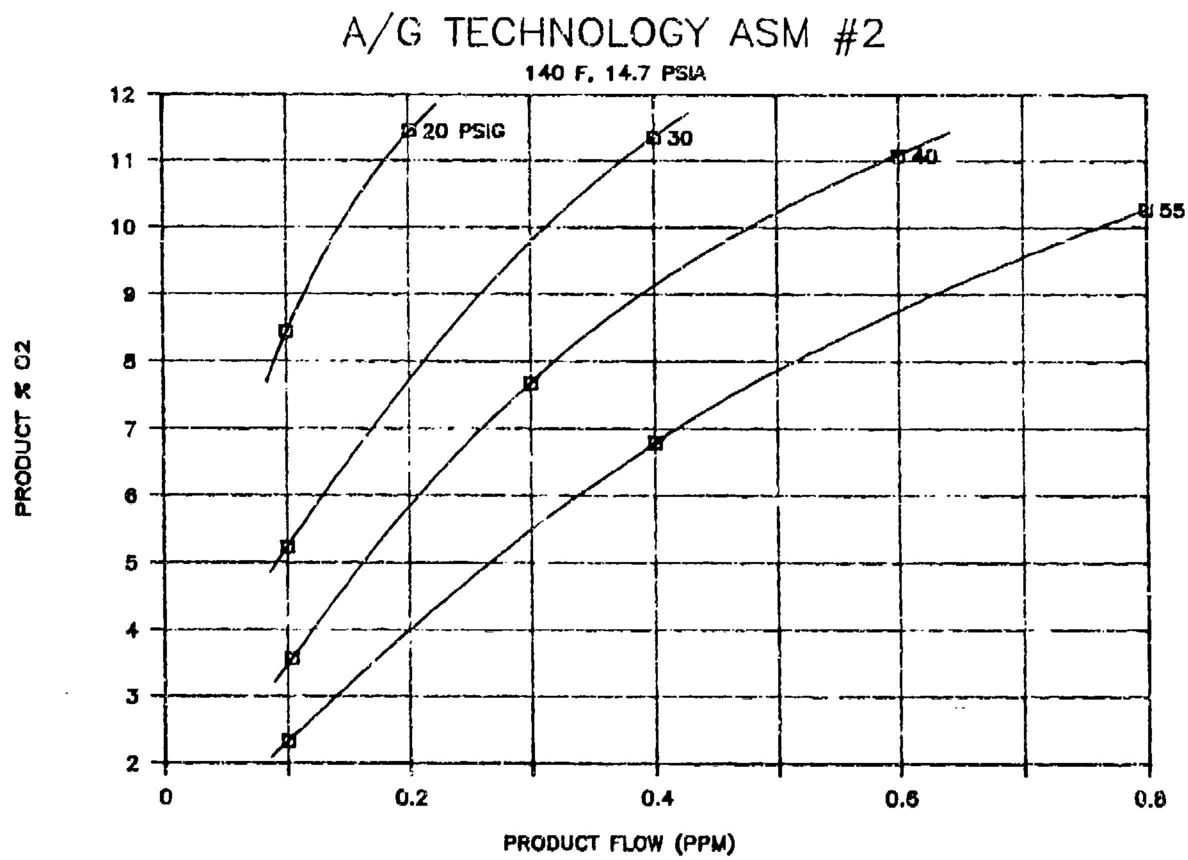
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

100°F, Nominal 5 PSIA

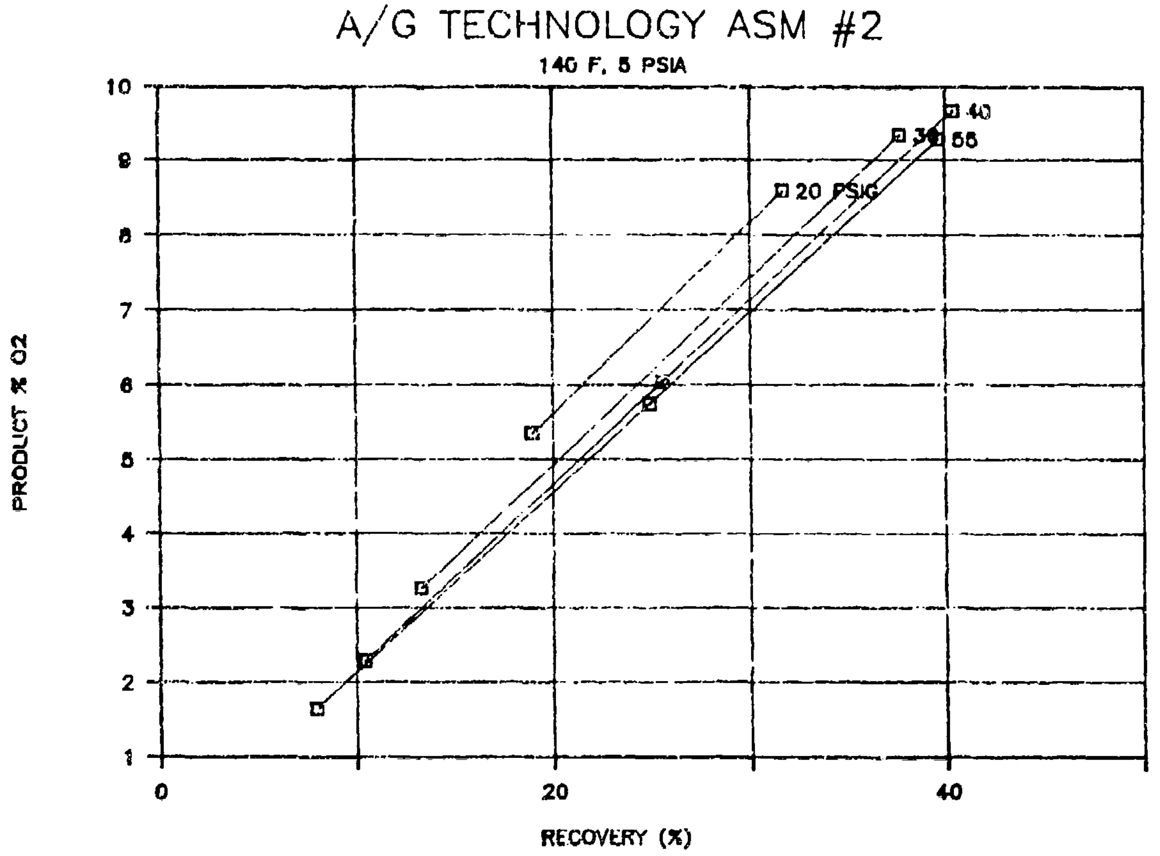
PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.98	5.04	100.3	0.199	9.28	40.92	1.66	0.485	99.4
20.04	5.06	100.3	0.099	5.67	25.62	1.15	0.387	99.3
30.04	5.01	100.3	0.099	3.24	18.54	1.06	0.534	99.4
30.06	4.99	100.2	0.400	10.01	47.20	2.21	0.848	99.3
39.91	5.03	100.3	0.599	10.31	49.65	2.54	1.207	99.2
39.92	5.02	100.2	0.301	6.40	33.56	1.60	0.896	99.4
39.97	5.03	100.1	0.100	2.13	14.79	1.00	0.677	99.5
54.99	5.05	100.1	0.100	1.35	11.14	0.98	0.899	100.3
55.04	5.00	100.0	0.400	5.97	32.50	1.68	1.232	100.3
54.97	5.07	100.1	0.799	9.83	48.49	2.65	1.649	99.4
70.01	5.00	100.0	1.200	10.68	52.52	3.16	2.286	98.4
69.73	5.01	99.8	0.601	6.75	36.17	1.88	1.661	99.0
70.10	4.97	99.7	0.202	2.26	16.40	1.14	1.230	99.6
89.97	5.08	99.6	0.201	1.72	13.10	1.13	1.532	100.9
90.00	5.05	99.6	0.800	6.95	36.33	2.04	2.200	100.0
90.18	5.07	99.8	1.604	10.91	53.23	3.44	3.013	97.8

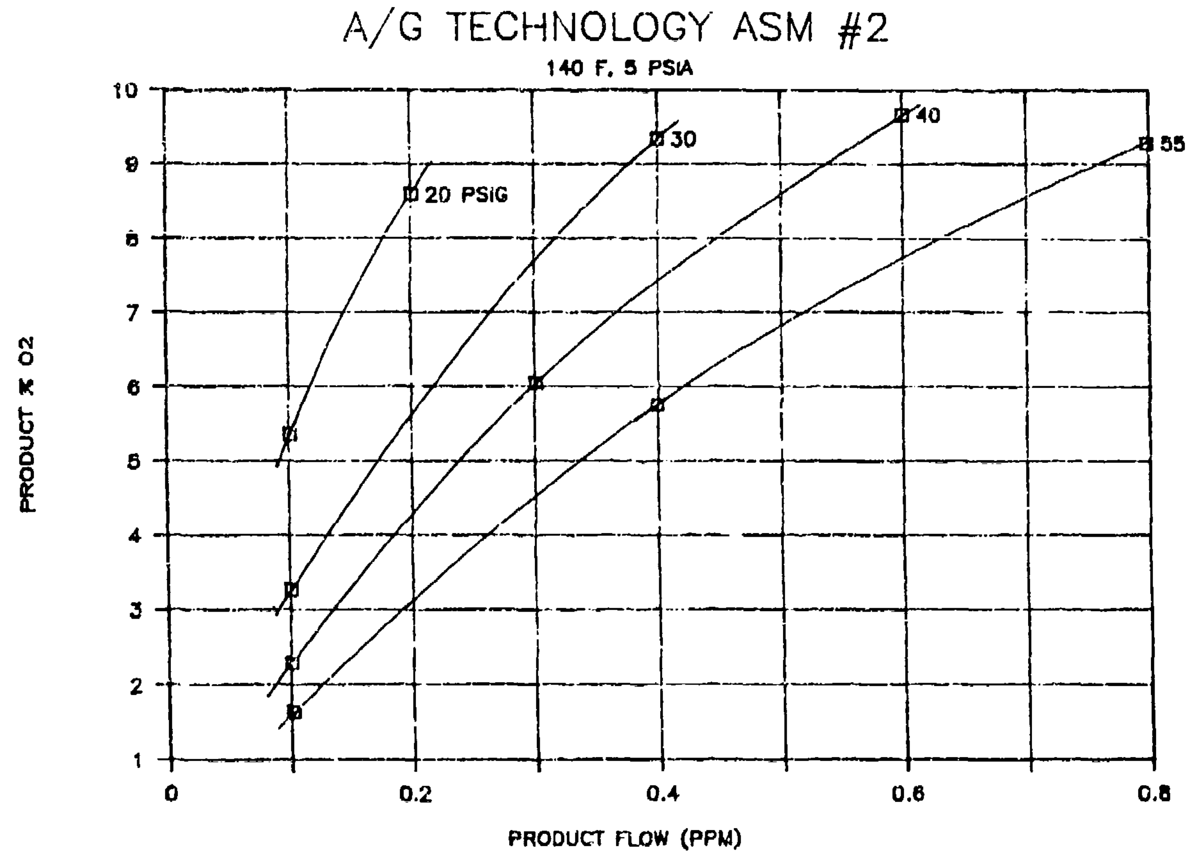
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

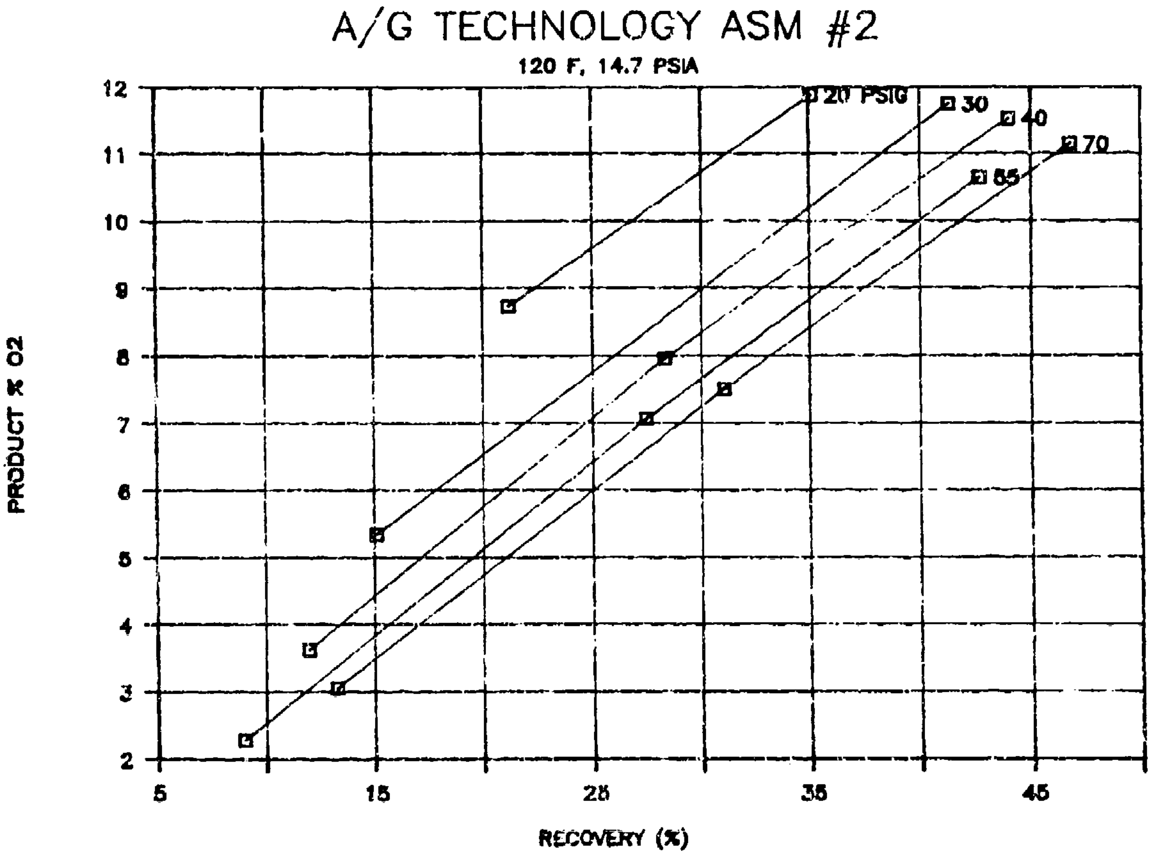


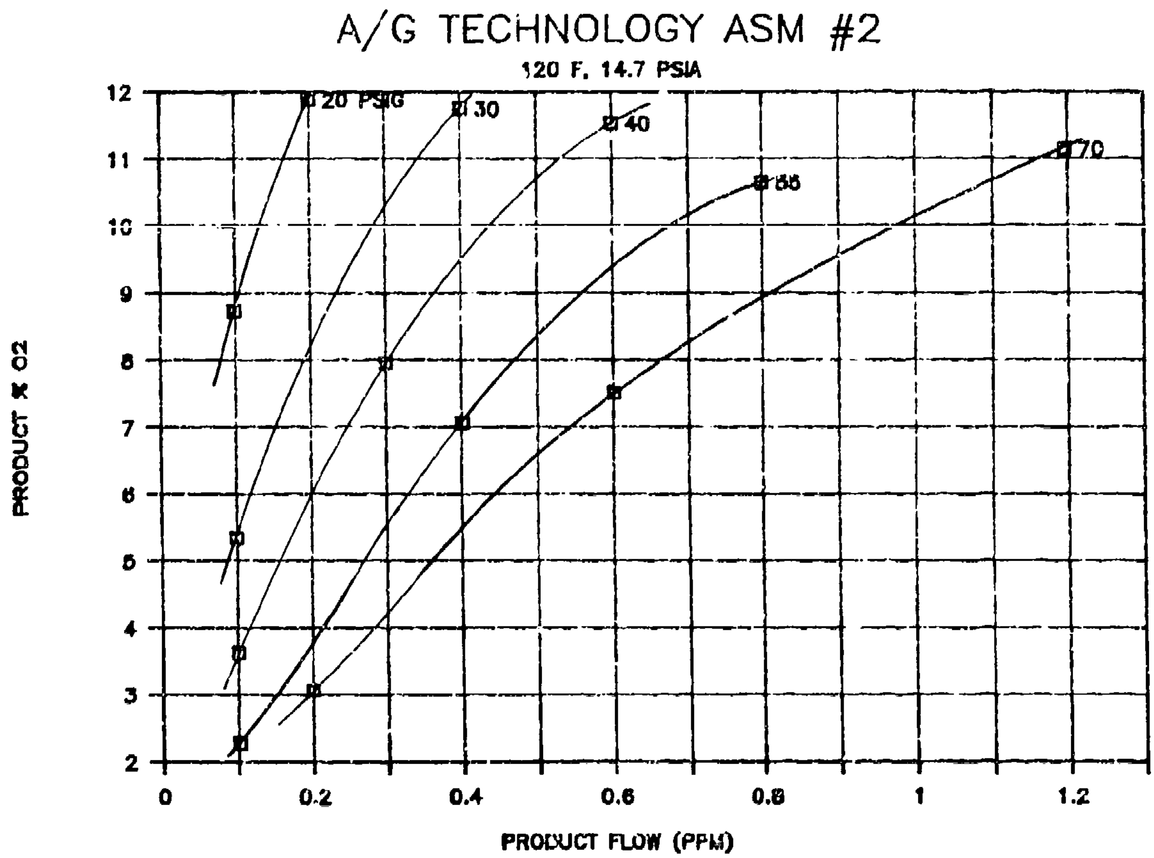


APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)

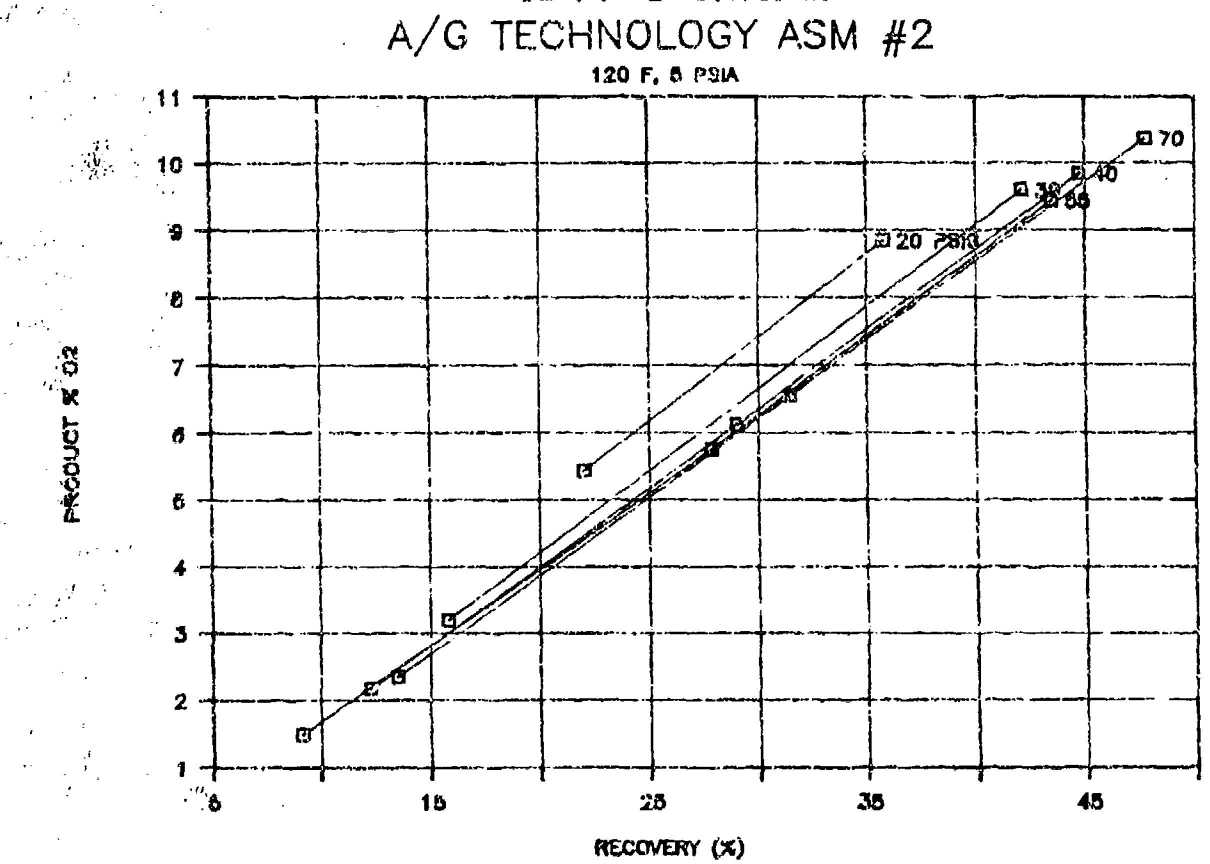


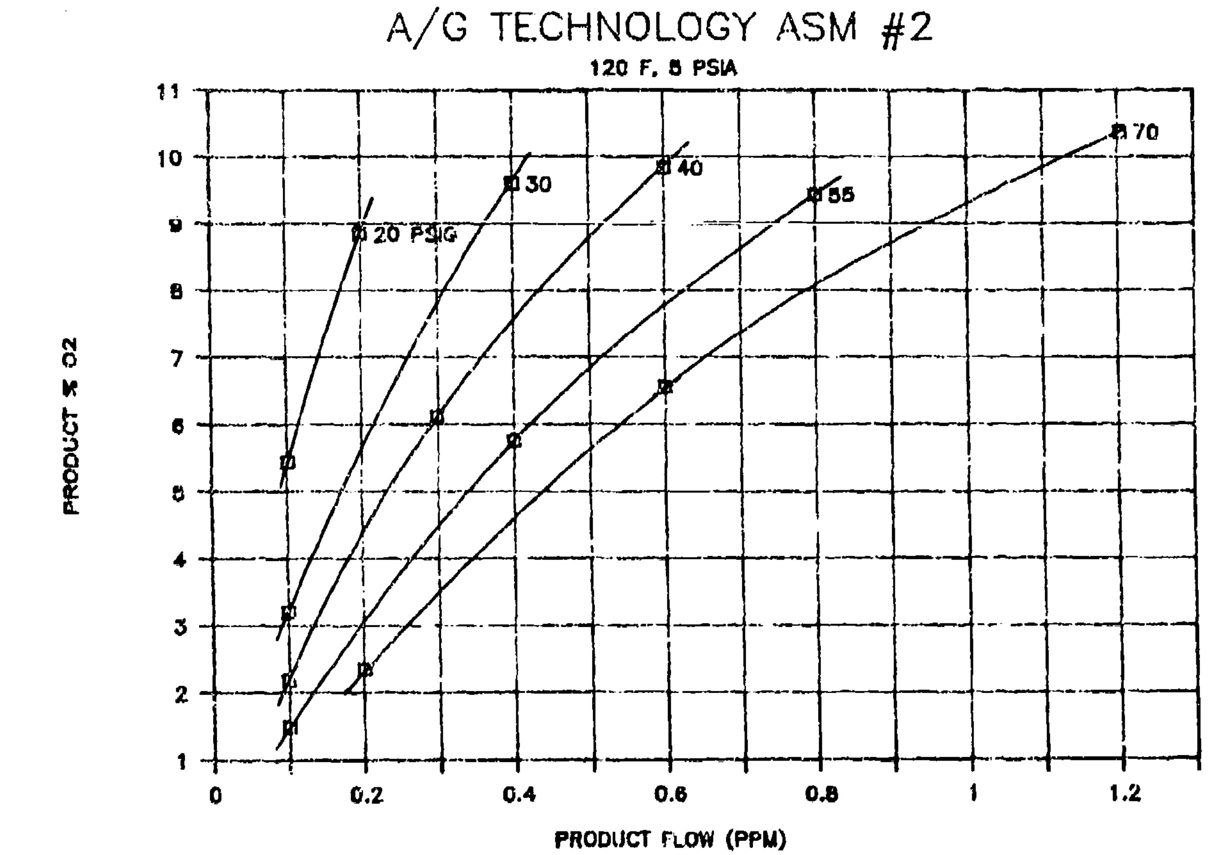



A/G TECHNOLOGY ASM #2
120 F, 14.7 PSIA
20 PSIG
30
40
55
70
PRODUCT % O2
RECOVERY (%)
2
3
4
5
6
7
8
9
10
11
12
5
15
25
35
45

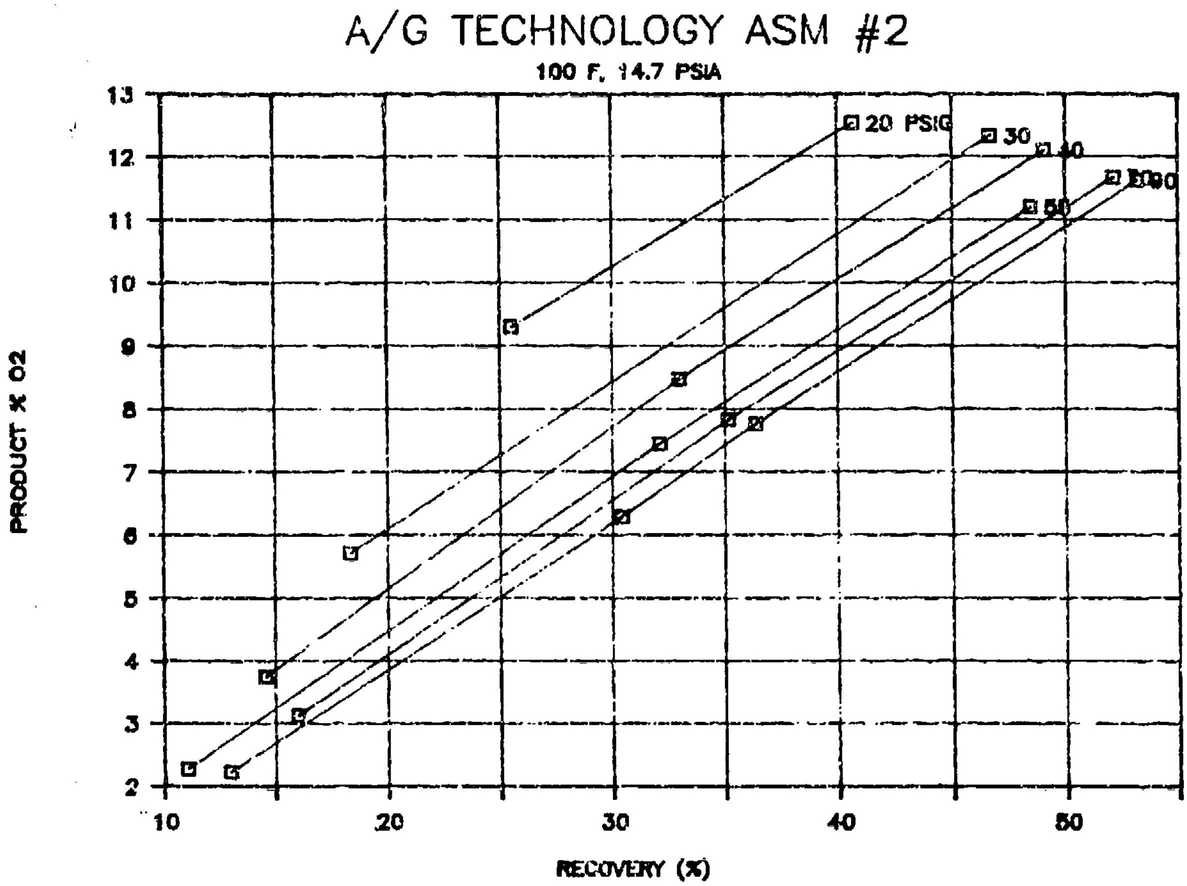

A/G TECHNOLOGY ASM #2
120 F, 14.7 PSIA
20 PSIG
30
40
55
70
PRODUCT % O2
PRODUCT FLOW (PPM)
2
3
4
5
6
7
8
9
10
11
12
0
0.2
0.4
0.6
0.8
1
1.2

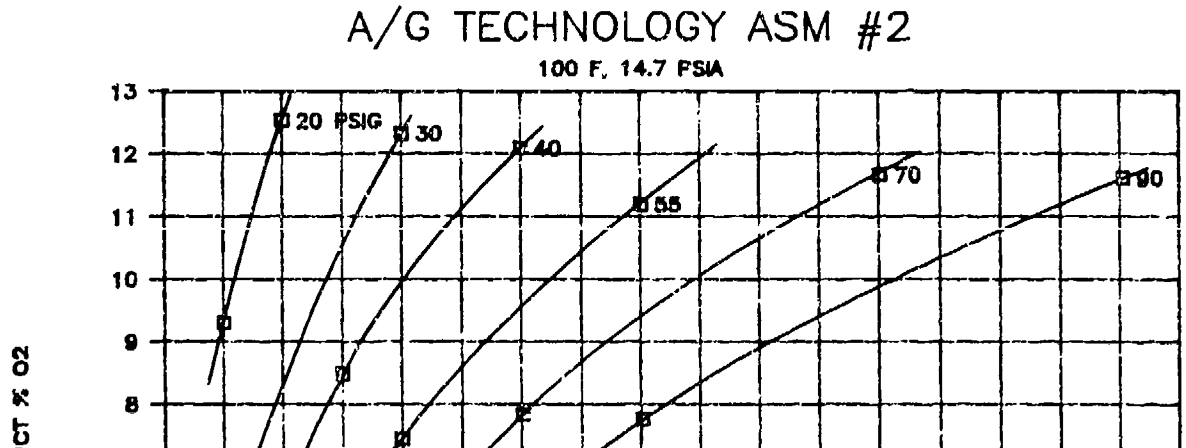
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)



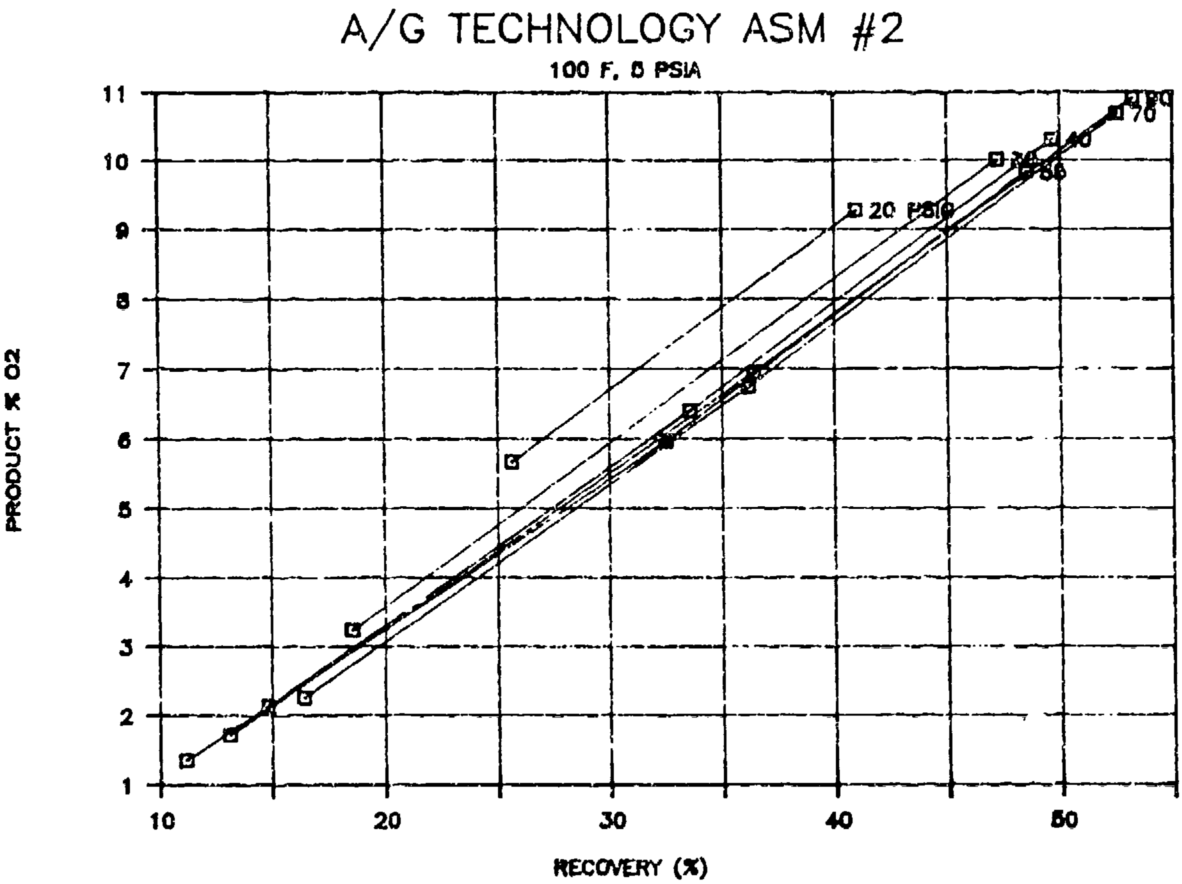


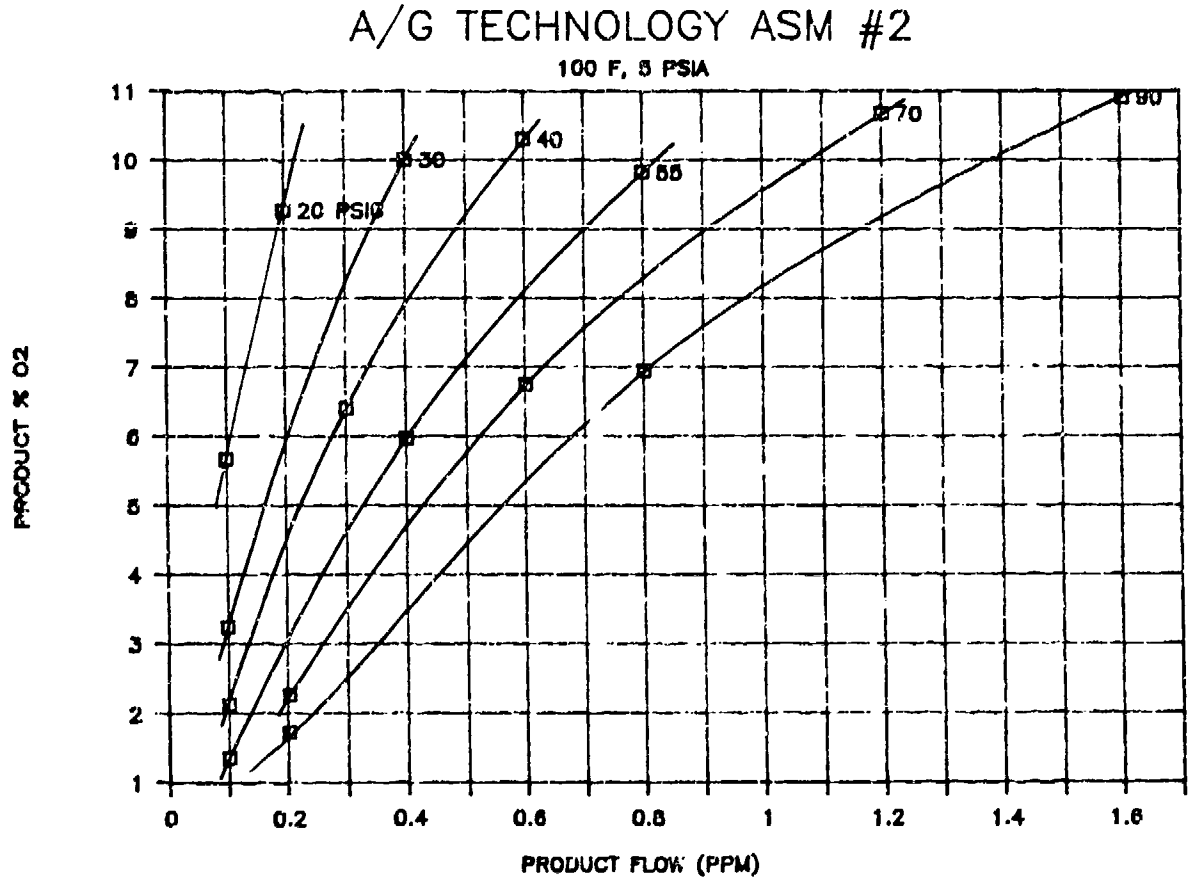
APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 2BH500201AL)





APPENDIX D
A/G TECHNOLOGY PERFORMANCE ENVELOPE DATA
ASM #2 (S/N 28H500201AL)





APPENDIX E - Permea Performance Envelope Data

This Appendix includes actual measured performance data for the Permea ASM presented in tabular and graphical form.

The definitions for the tabular data column headings are as follows:

- PASMIN = ASM inlet pressure, PSIG.
- PWASTE = ASM waste pressure, PSIA.
- T-ASM = ASM case temperature, ^{o}F.
- WPROD = Product or NEA mass flow rate, PPM or Lbs/Min.
- OXPROD = Product or NEA O_2 concentration, % by volume.
- O/I = Recovery or product flow/inlet flow, %.
- DP-ASM = ASM pressure drop or inlet - product pressure, PSID.
- WINLET = ASM inlet mass flow rate, PPM or Lbs/Min.
- TASMIN = ASM inlet air temperature, ^{o}F.

Note that some data (WINLET and O/I) are listed as NA (Not Available) in the tabular data. This resulted when inlet flow was below the range of the inlet flow meter. For the graphical data only, the missing data have been estimated using a model of waste flow (Appendix F).

The data on the following pages is organized according to the temperature and waste pressure. Each page contains all data (product flows and inlet pressures) collected at a particular temperature and waste pressure. The following index is offered to aid in locating specific data.

Temp (^{o}F)	Waste Pressure (PSIA)	Page #	
		Tab Data	Graph
200	14.7	E-2	E-12
200	5.0	E-3	E-13
175	14.7	E-4	E-14
175	5.0	E-5	E-15
150	14.7	E-6	E-16
150	5.0	E-7	E-17
120	14.7	E-8	E-18
120	10.0	E-9	E-19
120	5.0	E-10	E-20
120	2.0	E-11	E-21

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 200°F, 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.75	14.61	192.9	0.025	13.59	NA	2.67	NA	197.6
20.11	14.66	192.9	0.050	16.53	68.90	4.56	0.072	198.9
30.12	14.67	192.9	0.025	9.61	NA	2.44	NA	199.3
29.99	14.67	193.0	0.050	13.31	58.38	3.89	0.086	200.1
30.06	14.67	193.1	0.075	15.29	68.41	5.42	0.110	200.8
45.14	14.68	193.4	0.025	5.84	NA	2.23	NA	199.4
45.07	14.68	193.4	0.050	9.53	45.52	3.35	0.110	200.4
45.01	14.67	193.4	0.075	11.81	56.33	4.47	0.133	200.7
64.97	14.70	193.6	0.025	3.28	NA	2.07	NA	200.1
65.03	14.71	193.6	0.050	6.26	36.62	2.93	0.136	200.4
65.04	14.69	193.6	0.075	8.52	47.05	3.78	0.159	201.1
64.98	14.69	193.6	0.100	10.20	52.25	4.64	0.191	201.8
89.99	14.67	192.5	0.025	1.97	NA	2.01	NA	201.1
89.98	14.67	192.8	0.050	4.03	NA	2.65	NA	201.8
89.60	14.66	192.9	0.075	5.88	36.55	3.32	0.205	203.0
89.60	14.66	193.1	0.100	7.44	42.92	3.98	0.233	202.3
90.06	14.66	193.3	0.125	8.75	48.97	4.64	0.256	203.7
90.03	14.69	193.3	0.150	9.82	53.34	5.26	0.281	202.1

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 200°F, 5.0 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.82	4.99	192.2	0.025	9.92	50.80	3.84	0.050	198.2
19.96	4.99	192.2	0.050	14.13	69.85	6.74	0.071	199.5
30.02	5.01	191.8	0.025	6.04	38.53	3.13	0.065	196.8
30.04	5.00	191.8	0.050	10.42	57.54	5.14	0.087	199.1
29.99	4.98	192.2	0.075	13.10	66.07	7.14	0.113	196.0
45.12	5.01	192.7	0.025	3.54	29.50	2.62	0.085	197.4
45.02	4.98	192.6	0.050	6.94	44.67	3.98	0.111	197.0
45.22	4.98	192.7	0.075	9.48	55.90	5.37	0.135	197.9
65.34	5.03	194.0	0.025	1.92	23.00	2.28	0.109	197.2
65.04	5.00	194.0	0.050	4.39	36.33	3.28	0.137	197.6
65.11	5.00	194.6	0.075	6.62	47.29	4.25	0.159	197.9
65.23	5.01	194.8	0.101	8.38	53.02	5.26	0.190	198.3
90.03	5.00	195.1	0.025	1.19	21.50	2.13	0.116	197.5
89.98	4.99	195.3	0.050	2.85	28.94	2.88	0.174	198.2
89.78	4.99	195.2	0.075	4.50	37.40	3.59	0.200	199.1
90.11	4.99	195.4	0.100	6.04	43.99	4.35	0.228	200.0
90.11	4.99	195.4	0.125	7.35	49.22	5.08	0.255	200.5
89.98	4.99	195.5	0.150	8.48	53.71	5.82	0.279	200.4

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 175°F, 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.08	14.72	175.0	0.025	14.30	NA	2.35	NA	173.2
20.06	14.74	174.9	0.050	17.12	71.67	4.09	0.069	173.4
30.13	14.69	175.1	0.025	10.67	NA	2.09	NA	174.2
30.14	14.68	175.1	0.050	14.20	62.31	3.44	0.080	174.3
30.07	14.68	175.0	0.075	16.04	70.99	4.83	0.105	173.6
44.99	14.67	175.1	0.025	6.85	NA	1.84	NA	173.7
44.97	14.68	175.0	0.050	10.67	NA	2.87	NA	173.2
45.07	14.72	175.2	0.075	12.84	62.60	3.88	0.119	174.0
65.07	14.70	175.1	0.025	3.98	NA	1.67	NA	173.6
65.22	14.68	175.0	0.050	7.24	NA	2.45	NA	174.2
65.94	14.70	174.9	0.075	9.48	51.23	3.20	0.146	174.7
65.00	14.70	175.2	0.100	11.27	58.39	4.02	0.171	174.8
89.94	14.68	175.2	0.025	2.29	NA	1.54	NA	174.5
90.01	14.6	175.3	0.050	4.75	NA	2.16	NA	175.1
90.20	14.69	175.2	0.075	6.80	NA	2.75	NA	175.6
90.20	14.69	175.2	0.100	8.47	49.76	3.36	0.201	175.7
90.21	14.68	175.3	0.125	9.82	55.71	3.97	0.225	176.1
89.87	14.68	175.1	0.150	10.90	59.83	4.57	0.250	175.8

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 175°F, 5.0 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.01	4.97	175.0	0.025	10.82	56.04	3.38	0.045	174.7
20.22	4.96	174.9	0.050	14.70	72.56	6.00	0.069	173.8
29.91	5.02	175.0	0.025	7.04	NA	2.70	NA	173.9
29.92	5.01	174.8	0.050	11.32	61.72	4.52	0.081	174.3
29.94	5.00	175.0	0.075	13.80	71.64	6.45	0.105	173.7
45.05	4.98	175.3	0.025	4.06	NA	2.21	NA	173.6
45.01	4.96	175.1	0.050	7.85	51.60	3.48	0.097	174.5
44.92	4.98	175.2	0.075	10.52	60.28	4.75	0.124	173.9
64.87	5.00	175.1	0.025	2.25	NA	1.93	NA	175.2
64.92	5.03	175.3	0.050	5.08	41.44	2.86	0.121	175.9
64.85	5.03	175.4	0.075	7.44	50.42	3.78	0.149	176.9
64.82	5.00	175.6	0.100	9.19	57.86	4.72	0.174	177.5
89.87	5.00	175.5	0.025	1.33	NA	1.74	NA	176.9
89.94	5.00	175.6	0.050	3.20	NA	2.41	NA	177.9
90.02	4.98	175.3	0.075	5.29	43.16	3.05	0.174	175.1
90.01	5.00	175.2	0.100	6.92	49.93	3.71	0.200	176.1
90.01	4.99	175.3	0.125	8.32	54.52	4.39	0.228	175.8
89.87	5.00	175.1	0.149	9.44	60.06	5.05	0.248	176.7

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 150°F, 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.98	14.71	149.0	0.025	15.56	NA	1.97	NA	147.1
19.99	14.71	149.2	0.050	17.98	80.14	3.58	0.062	147.2
30.03	14.68	149.3	0.025	11.95	NA	1.67	NA	147.7
30.10	14.68	149.3	0.050	15.47	NA	2.97	NA	147.1
30.01	14.63	149.2	0.075	17.04	78.69	4.24	0.095	147.5
44.89	14.73	149.4	0.025	8.11	NA	1.45	NA	146.5
44.92	14.70	149.3	0.050	12.15	NA	2.42	NA	147.7
45.07	14.67	149.1	0.075	14.23	70.32	3.35	0.107	147.9
65.13	14.67	149.3	0.025	4.89	NA	1.25	NA	147.1
65.11	14.68	149.7	0.050	8.68	NA	1.97	NA	147.3
64.98	14.68	149.3	0.075	11.15	NA	2.71	NA	147.6
64.99	14.67	149.2	0.100	12.74	67.06	3.42	0.149	147.8
90.04	14.67	149.7	0.025	2.79	NA	1.13	NA	147.7
90.13	14.65	149.5	0.050	5.84	NA	1.68	NA	148.3
89.99	14.66	149.5	0.075	8.22	NA	2.24	NA	149.1
89.98	14.67	149.5	0.100	10.03	NA	2.81	NA	148.4
89.92	14.67	149.4	0.125	11.31	63.79	3.34	0.195	149.1
89.97	14.68	149.4	0.150	12.37	68.26	3.91	0.219	149.5

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 150°F, 5.0 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.98	4.96	149.2	0.025	12.18	NA	2.82	NA	148.1
20.08	5.00	149.4	0.050	15.95	80.07	5.29	0.063	148.9
29.95	5.01	149.6	0.025	8.42	NA	2.19	NA	14[illegible].3
30.17	4.99	149.4	0.050	12.76	71.02	3.89	0.071	147.1
29.98	4.98	149.4	0.075	14.97	73.15	5.66	0.096	148.2
44.89	5.03	149.3	0.025	5.09	NA	1.77	NA	148.8
45.05	5.01	149.5	0.050	9.21	59.12	2.94	0.084	149.5
45.05	5.01	149.2	0.075	11.84	68.51	4.13	0.110	150.1
65.11	5.00	149.6	0.025	2.85	NA	1.46	NA	148.8
65.04	5.00	149.6	0.050	6.32	NA	2.28	NA	148.8
64.98	4.99	149.3	0.075	8.91	59.28	3.12	0.126	149.3
65.09	5.01	149.6	0.100	10.75	64.76	3.95	0.154	149.4
90.02	5.01	149.5	0.025	[illegible].66	NA	1.28	NA	149.1
89.96	5.00	149.7	0.050	4.17	NA	1.91	NA	149.1
90.08	5.01	149.8	0.075	6.38	NA	2.51	NA	149.5
90.08	5.02	149.4	0.100	8.18	57.98	3.14	0.173	150.0
89.94	5.02	149.4	0.125	9.61	62.71	3.75	0.199	150.0
89.89	5.00	149.7	0.150	10.81	66.86	4.39	0.224	150.8

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 120°F, 14.7 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.96	14.65	119.0	0.025	16.78	NA	1.71	NA	119.3
20.09	14.66	118.9	0.050	18.70	86.01	3.18	0.058	119.6
30.12	14.64	118.8	0.025	13.74	NA	1.41	NA	118.1
30.04	14.66	118.9	0.050	16.73	NA	2.57	NA	118.5
30.03	14.67	119.1	0.075	18.00	85.37	3.73	0.088	119.0
45.00	14.67	119.0	0.025	10.07	NA	1.18	NA	119.3
45.01	14.66	119.1	0.050	13.82	NA	2.05	NA	118.8
45.00	14.67	118.8	0.075	15.67	NA	2.91	NA	119.1
64.98	14.67	119.0	0.024	6.43	NA	0.98	NA	118.5
64.99	14.66	118.9	0.050	10.53	NA	1.64	NA	118.6
64.99	14.66	119.1	0.075	12.87	NA	2.30	NA	119.1
65.05	14.66	119.1	0.100	14.35	74.44	2.96	0.134	120.2
89.95	14.68	119.3	0.025	3.98	NA	0.86	NA	119.3
89.95	14.68	119.1	0.050	7.64	NA	1.37	NA	119.7
89.89	14.67	119.3	0.075	10.05	NA	1.87	NA	120.2
89.89	14.67	119.1	0.100	11.79	NA	2.37	NA	120.4
89.78	14.65	119.0	0.125	13.08	NA	2.87	NA	120.8
89.99	14.64	119.1	0.150	14.08	76.14	3.38	0.197	121.0

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 120°F, 10.0 PSIA

PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD ($\%O_2$)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
19.94	10.06	119.0	0.025	15.89	NA	2.00	NA	118.2
19.97	10.10	118.9	0.050	18.24	85.50	3.69	0.058	117.3
30.04	10.05	118.9	0.026	12.79	NA	1.58	NA	119.0
29.89	10.06	118.8	0.050	16.09	NA	2.85	NA	119.1
30.08	10.01	118.3	0.075	17.46	85.56	4.11	0.087	118.5
45.12	9.93	117.0	0.025	8.81	NA	1.24	NA	117.5
45.08	9.97	119.1	0.050	12.93	NA	2.17	NA	118.3
44.98	10.01	119.1	0.075	15.02	78.07	3.12	0.096	119.4
64.95	9.95	118.2	0.025	5.59	NA	1.01	NA	119.4
64.99	9.97	119.2	0.050	9.82	NA	1.73	NA	118.8
65.09	10.01	118.6	0.075	12.20	NA	2.39	NA	119.3
65.32	9.98	118.8	0.101	13.81	75.51	3.10	0.133	118.7
90.05	9.97	119.2	0.025	3.30	NA	0.90	NA	118.4
89.97	9.99	119.0	0.050	6.82	NA	1.43	NA	118.8
90.01	10.01	118.9	0.075	9.26	NA	1.94	NA	119.2
89.97	9.98	118.8	0.100	11.07	NA	2.47	NA	119.3
90.02	10.01	118.9	0.125	12.43	71.64	3.00	0.174	119.4
89.97	9.98	118.7	0.150	13.45	75.49	3.52	0.198	119.2

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 120°F, 5.0 PSIA

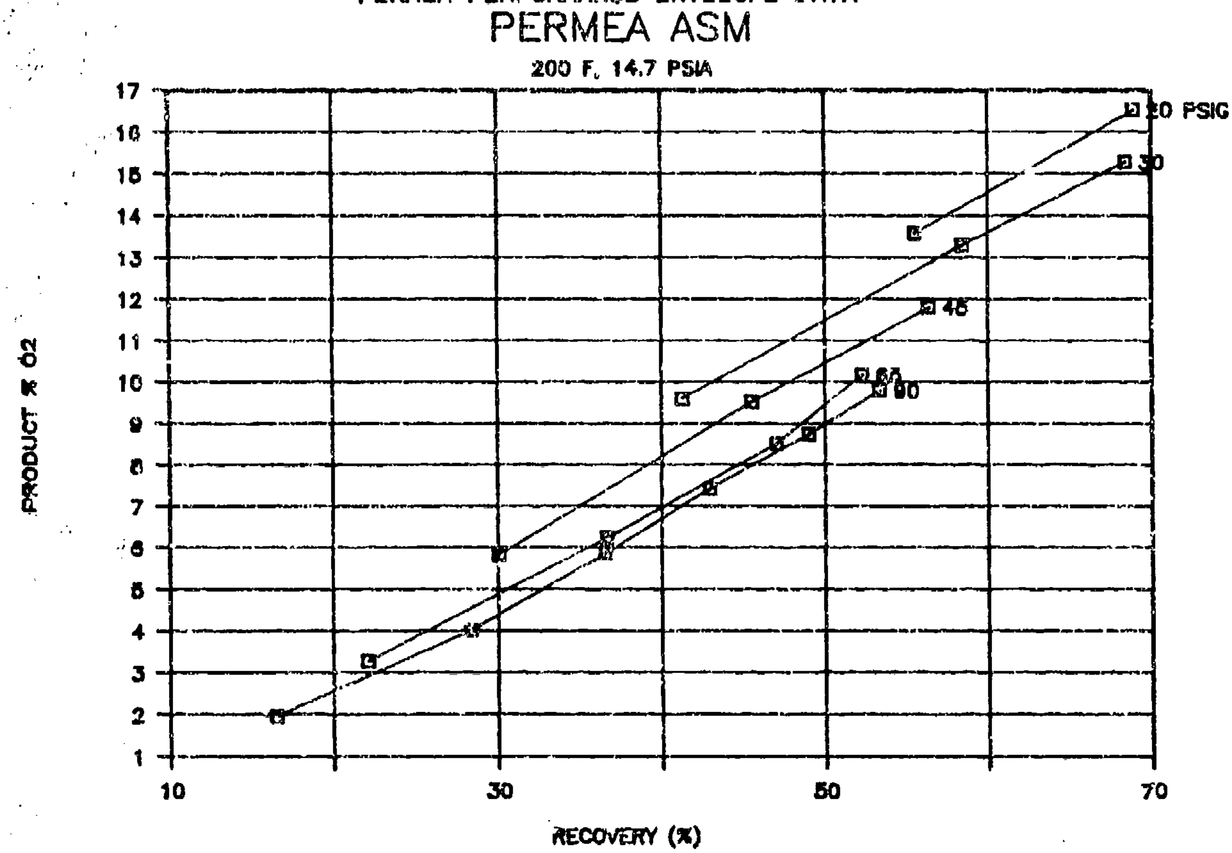
PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.10	4.98	119.7	0.025	13.75	NA	2.29	NA	115.4
20.02	4.99	119.5	0.050	17.04	87.80	4.48	0.057	115.5
29.91	4.99	119.6	0.025	10.41	NA	1.81	NA	116.2
30.08	5.08	119.6	0.050	14.47	78.26	3.27	0.064	116.8
30.00	5.03	119.6	0.075	16.36	84.94	4.84	0.088	117.8
30.01	5.03	119.7	0.100	17.46	88.76	6.49	0.113	118.9
44.99	5.01	119.6	0.025	7.01	NA	1.38	NA	116.7
45.03	4.97	119.4	0.050	11.32	NA	2.42	NA	117.0
44.95	4.99	119.8	0.075	13.70	77.40	3.47	0.097	118.2
45.01	4.99	119.5	0.100	15.14	82.18	4.51	0.121	119.1
44.88	4.99	119.5	0.125	16.15	85.14	5.61	0.146	119.9
45.08	5.05	119.5	0.150	16.90	87.58	6.75	0.171	121.3
64.97	5.01	119.6	0.025	4.32	NA	1.09	NA	118.7
64.93	4.98	119.4	0.050	8.37	NA	1.83	NA	118.1
64.96	5.02	119.5	0.075	10.95	NA	2.57	NA	118.8
65.03	5.02	119.5	0.100	12.68	75.03	3.31	0.133	119.6
64.95	5.03	119.3	0.125	13.94	79.20	4.08	0.158	120.4
65.05	5.00	119.7	0.150	14.84	82.38	4.83	0.182	121.3
90.12	5.04	119.4	0.025	2.39	NA	0.90	NA	116.8
90.03	5.00	119.4	0.050	5.82	NA	1.46	NA	117.6
90.12	4.98	119.4	0.075	8.43	NA	2.02	NA	118.8
89.97	5.00	119.5	0.100	10.23	NA	2.56	NA	119.7
89.92	4.98	119.6	0.125	11.71	72.38	3.12	0.173	120.2
90.11	4.99	119.5	0.150	12.78	75.72	3.65	0.198	121.3

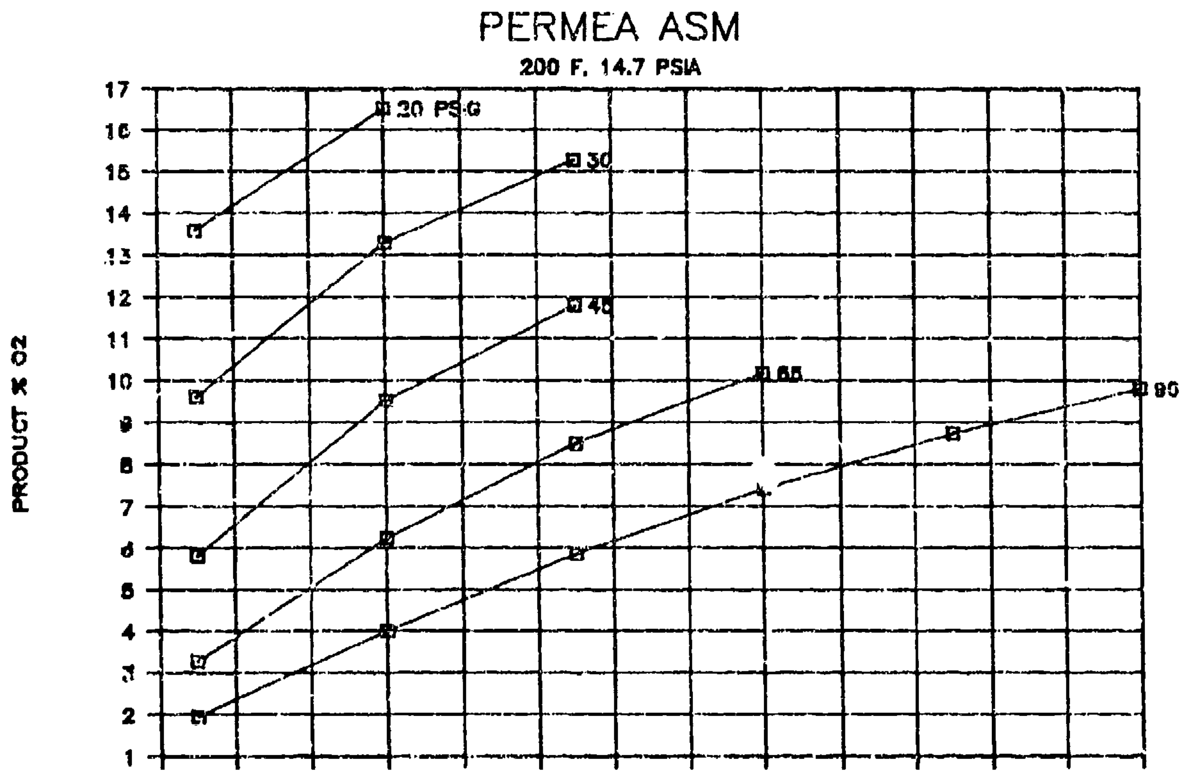
APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

Nominal 120°F, 2.0 PSIA

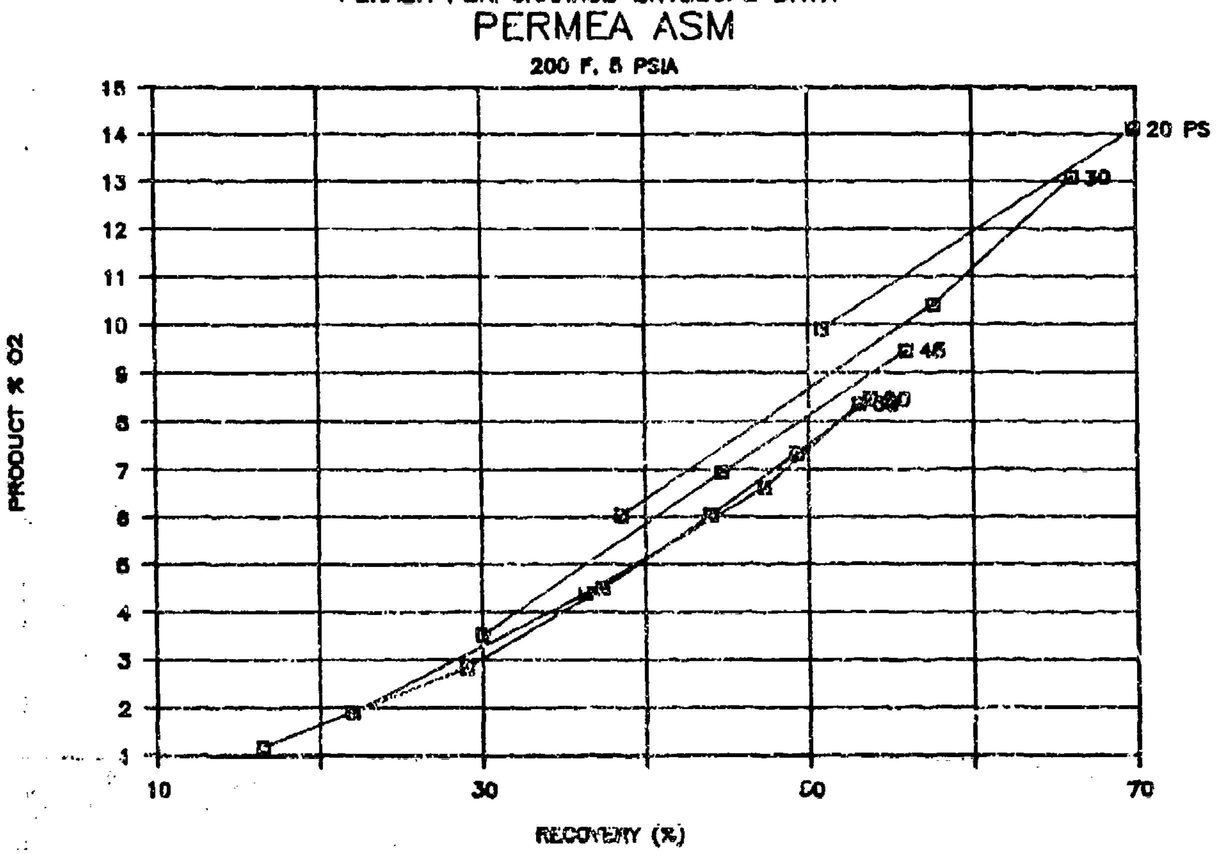
PASMIN (PSIG)	PWASTE (PSIA)	T-ASM (°F)	WPROD (PPM)	OXPROD (%O_2)	O/I (%)	DP-ASM (PSID)	WINLET (PPM)	TASMIN (°F)
20.00	2.01	119.6	0.064	16.69	92.71	6.60	0.069	119.6
20.14	2.00	119.5	0.050	15.78	66.15	5.21	0.058	121.6
19.95	2.06	119.5	0.025	12.14	NA	2.69	NA	112.3
30.00	2.02	119.6	0.025	8.77	NA	1.97	NA	113.9
30.08	2.02	119.8	0.050	13.11	76.43	3.66	0.065	117.2
29.95	2.01	119.6	0.075	15.36	83.42	5.44	0.090	117.0
44.97	2.02	119.8	0.025	5.34	NA	1.50	NA	114.8
45.04	2.02	119.8	0.050	10.10	NA	2.59	NA	114.4
44.98	2.02	119.8	0.075	12.74	76.29	3.73	0.099	114.1
44.99	2.01	119.6	0.100	14.40	81.30	4.87	0.123	113.9
44.99	2.01	119.6	0.125	15.63	85.11	6.03	0.147	112.1
60.00	2.02	119.8	0.025	3.76	NA	1.20	NA	120.8
65.02	2.02	119.5	0.050	7.72	NA	1.89	NA	106.0
64.96	2.01	119.4	0.075	10.49	NA	2.65	NA	105.2
64.96	2.01	119.4	0.100	12.37	75.24	3.42	0.133	104.6
65.03	2.01	119.2	0.125	13.70	79.61	4.18	0.157	104.5
65.04	2.00	118.9	0.150	14.79	83.01	4.91	0.180	103.6
89.97	1.99	119.0	0.025	2.29	NA	0.90	NA	117.1
90.12	2.04	119.2	0.050	5.42	NA	1.49	NA	118.0
89.88	2.02	119.1	0.075	7.99	NA	2.04	NA	118.3
89.95	2.01	119.2	0.100	9.89	NA	2.62	NA	119.4
89.95	2.01	119.1	0.125	11.27	71.70	3.18	0.174	120.6
89.95	2.01	119.3	0.150	12.35	75.68	3.79	0.198	121.5

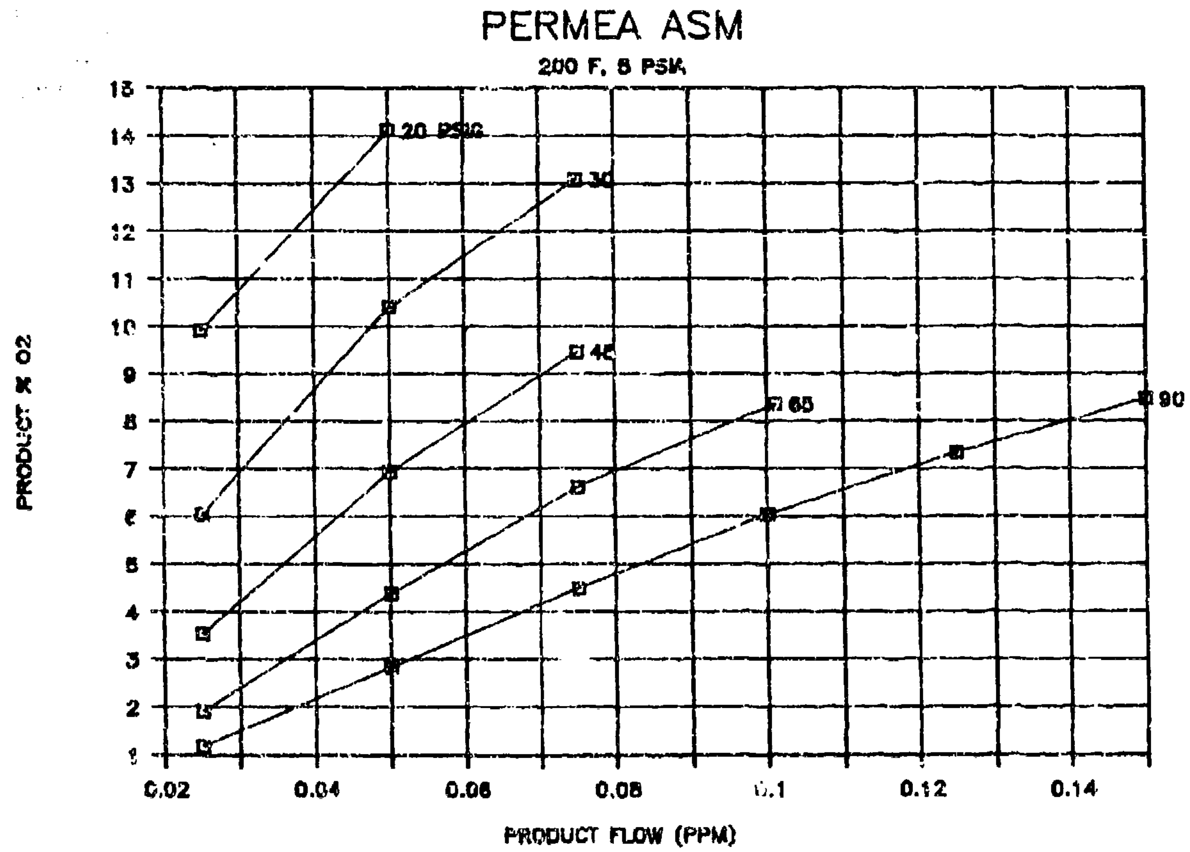
APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA





APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

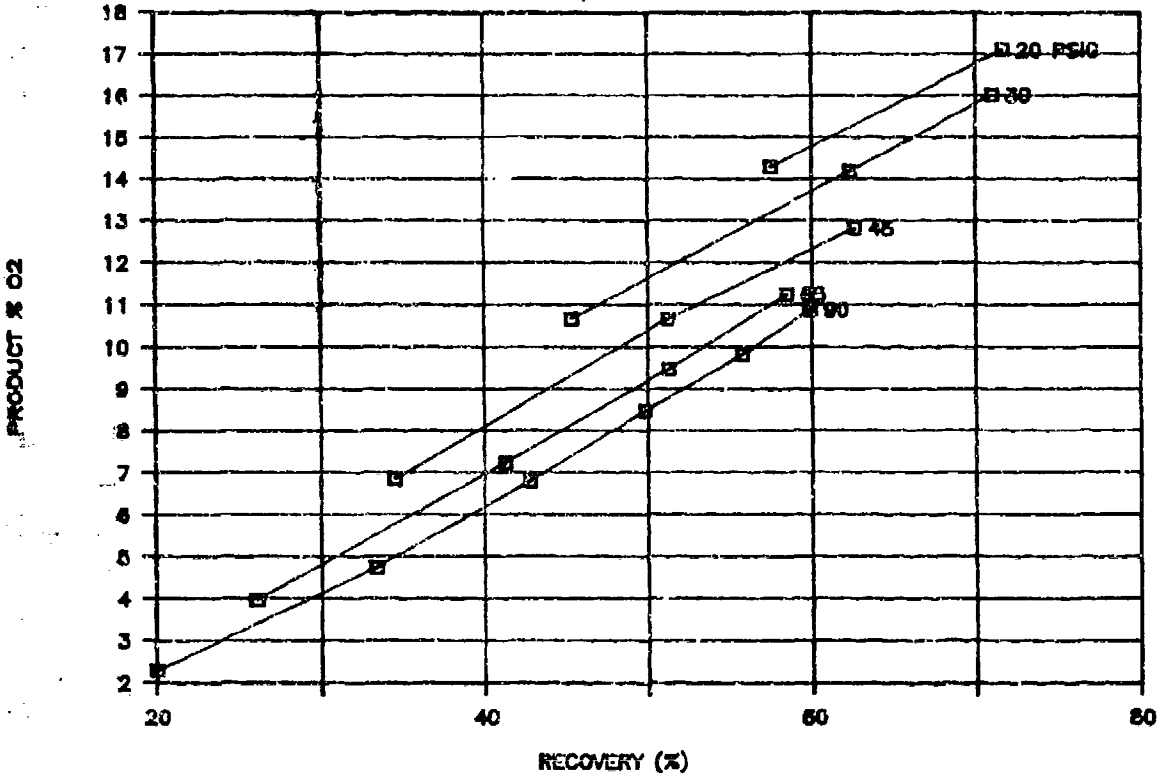




PERMEA PERFORMANCE ENVELOPE DATA

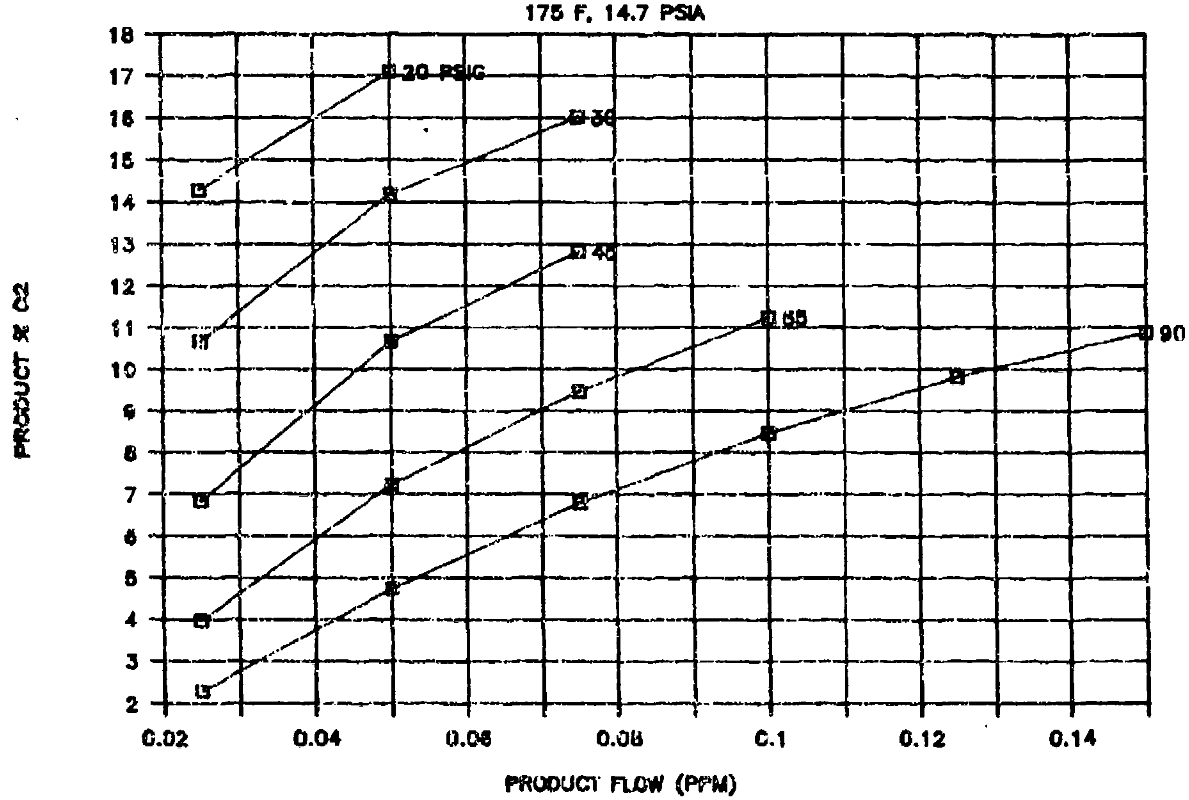
PERMEA ASM

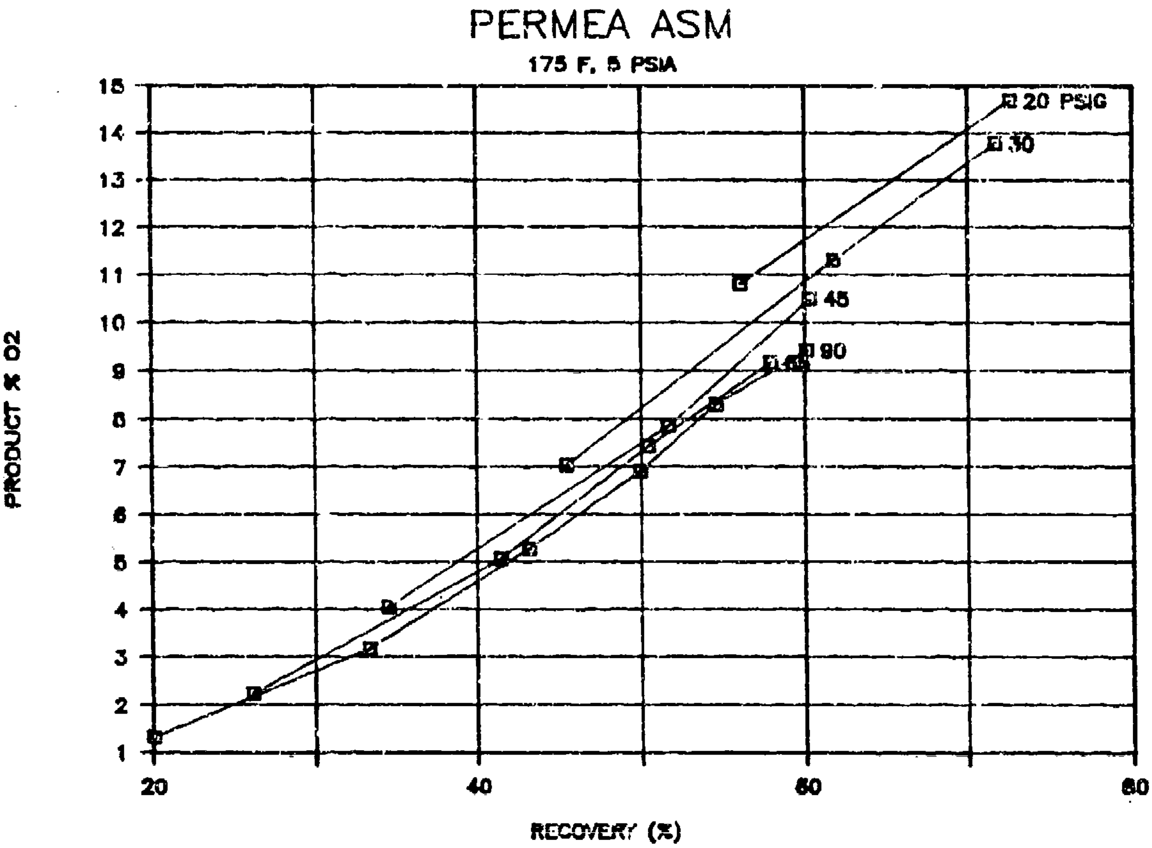
175 F, 14.7 PSIA

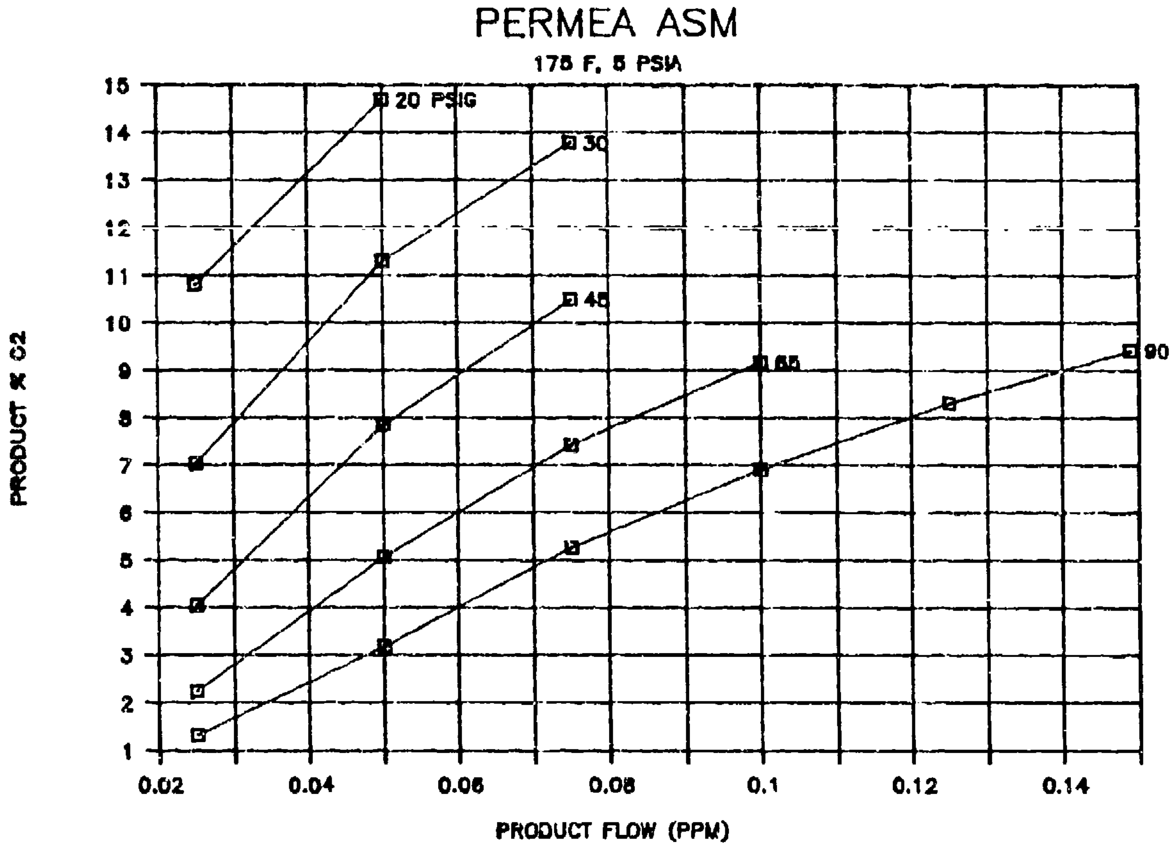


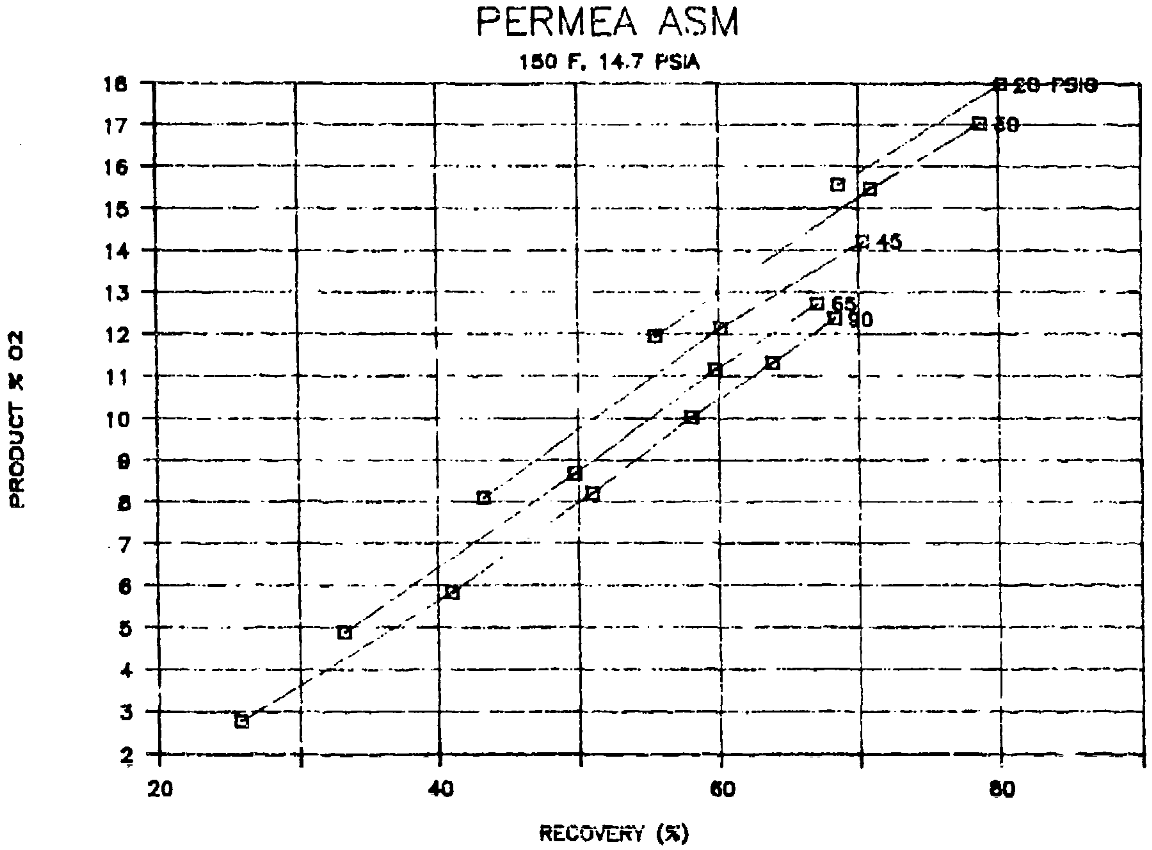
PERMEA ASM

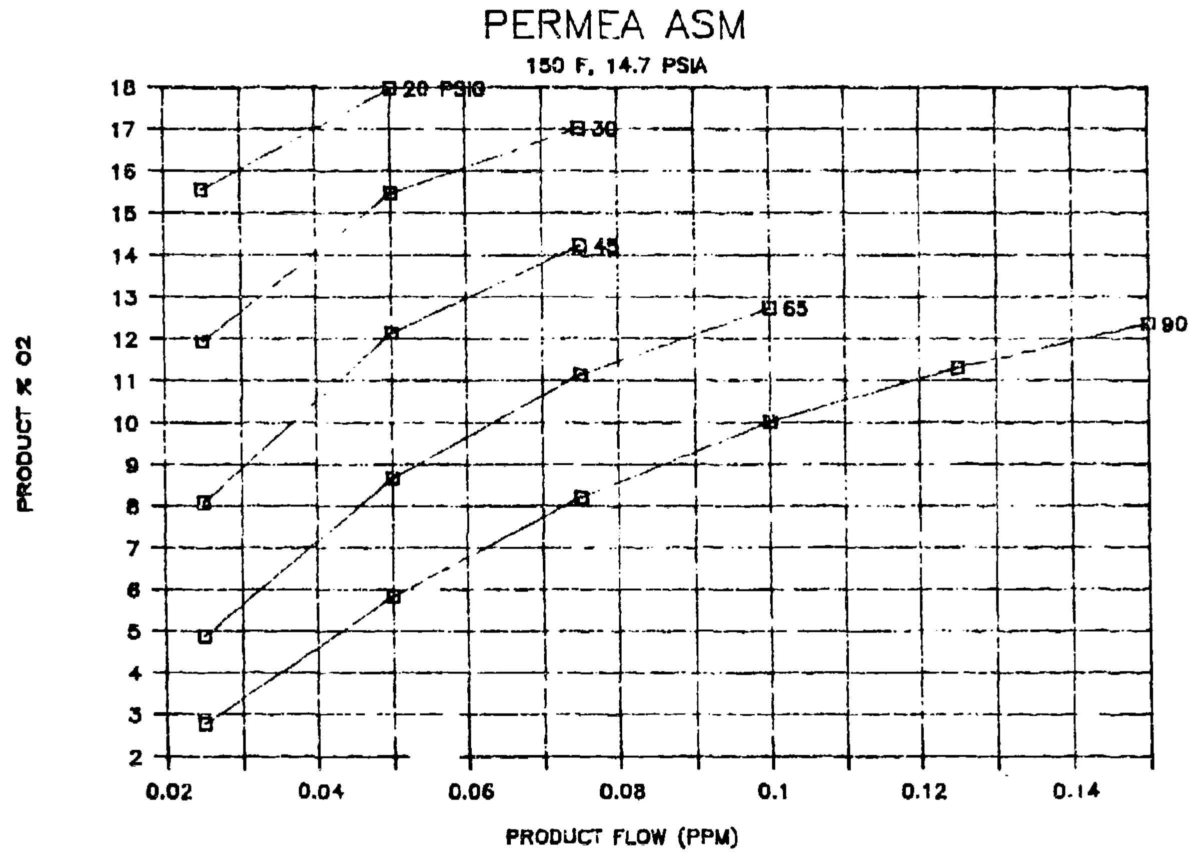
175 F, 14.7 PSIA



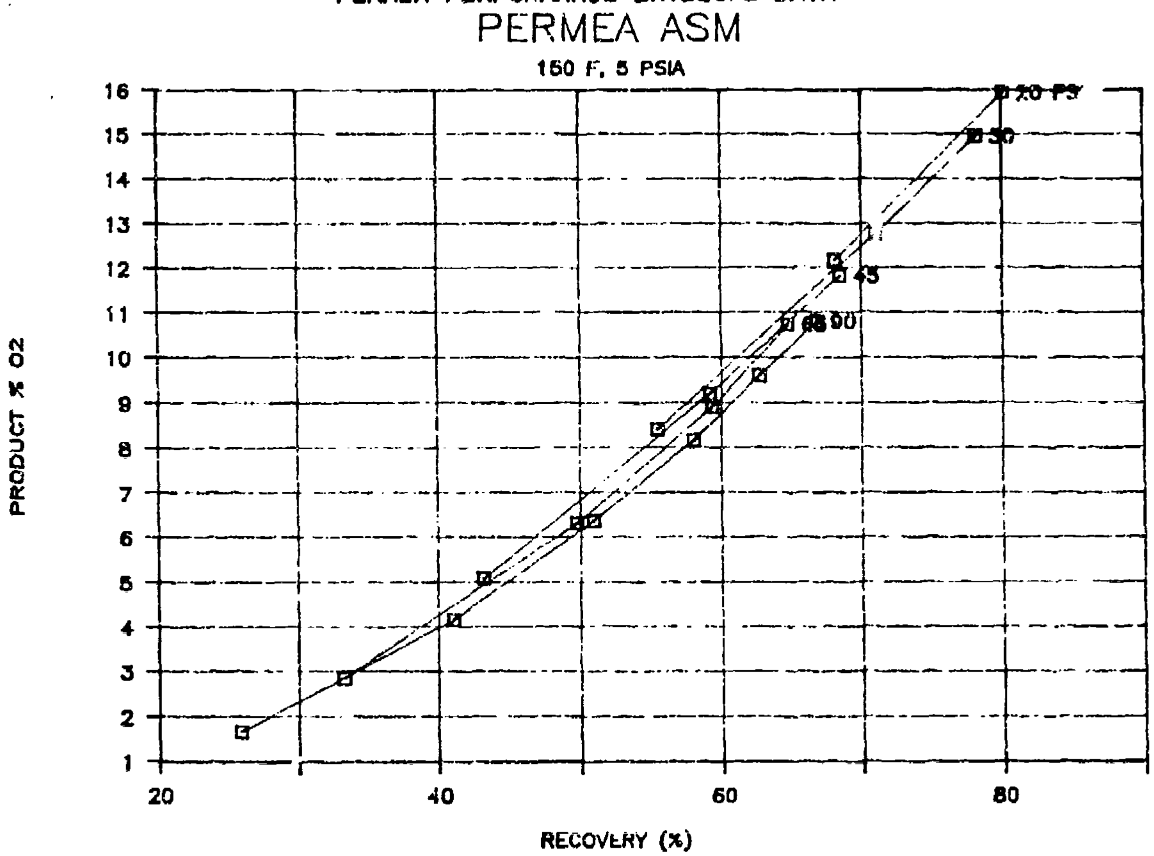

PERMEA ASM
175 F, 5 PSIA
20 PSIG
30
45
65
90
PRODUCT % O2
RECOVERY (%)
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

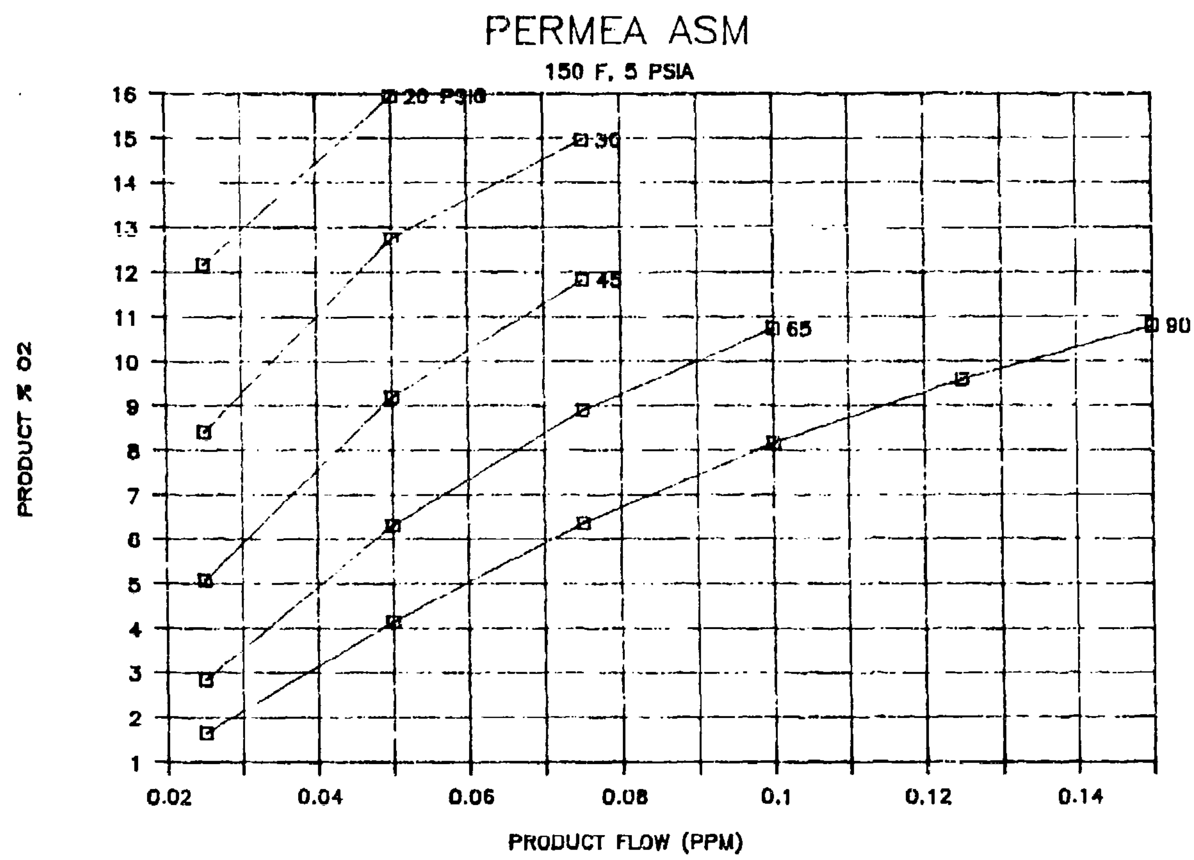

PERMEA ASM
175 F, 5 PSIA
20 PSIG
30
45
65
90
PRODUCT % O2
PRODUCT FLOW (PPM)
0.02
0.04
0.06
0.08
0.1
0.12
0.14
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


PERMEA ASM
150 F, 14.7 PSIA
20 PSIG
30
45
65
90
PRODUCT % O2
RECOVERY (%)


PERMEA ASM
150 F, 14.7 PSIA
20 PSIG
30
45
65
90
PRODUCT % O2
PRODUCT FLOW (PPM)

APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA



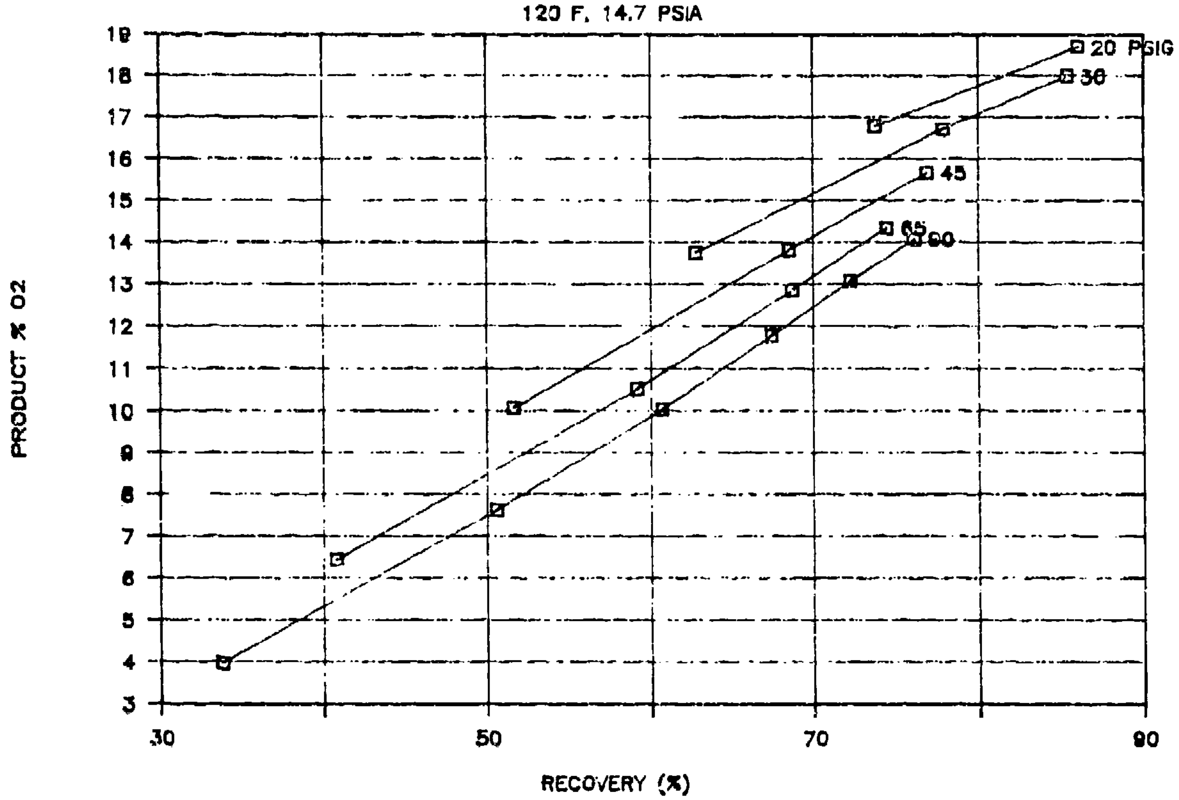


APPENDIX E

PERMEA PERFORMANCE ENVELOPE DATA

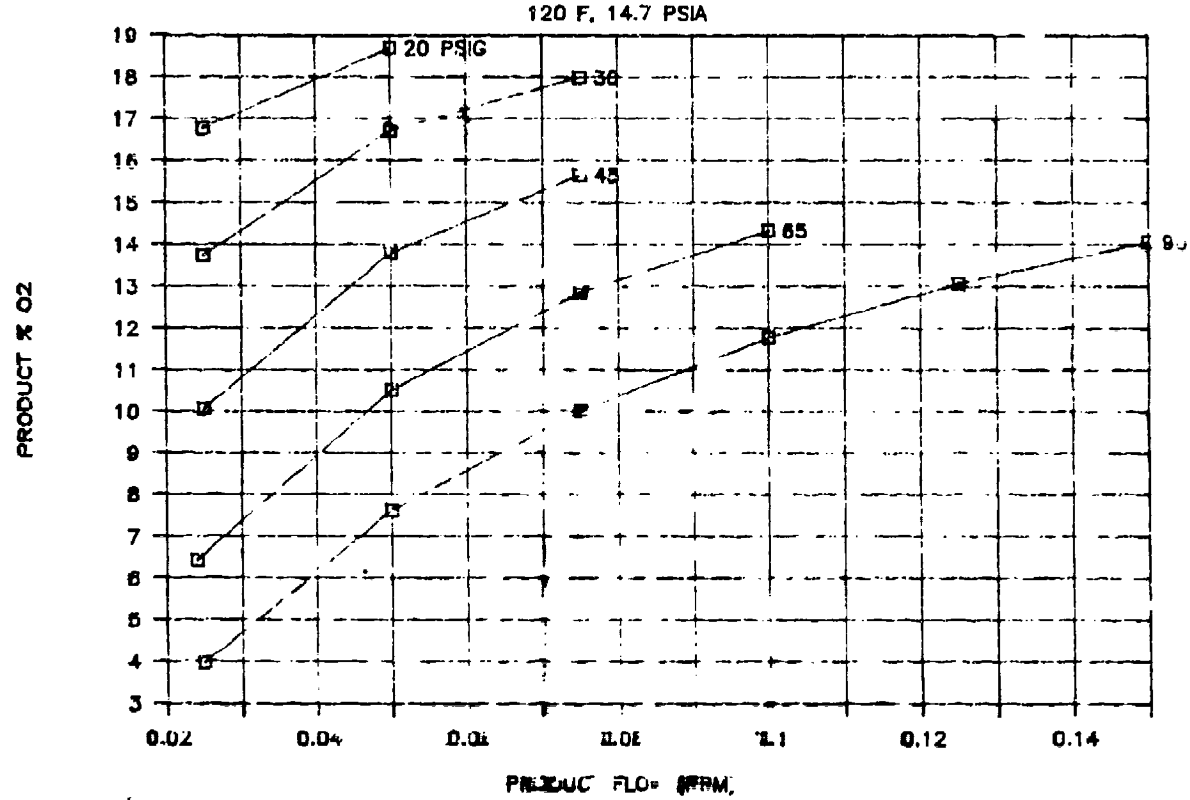
PERMEA ASM

120 F, 14.7 PSIA

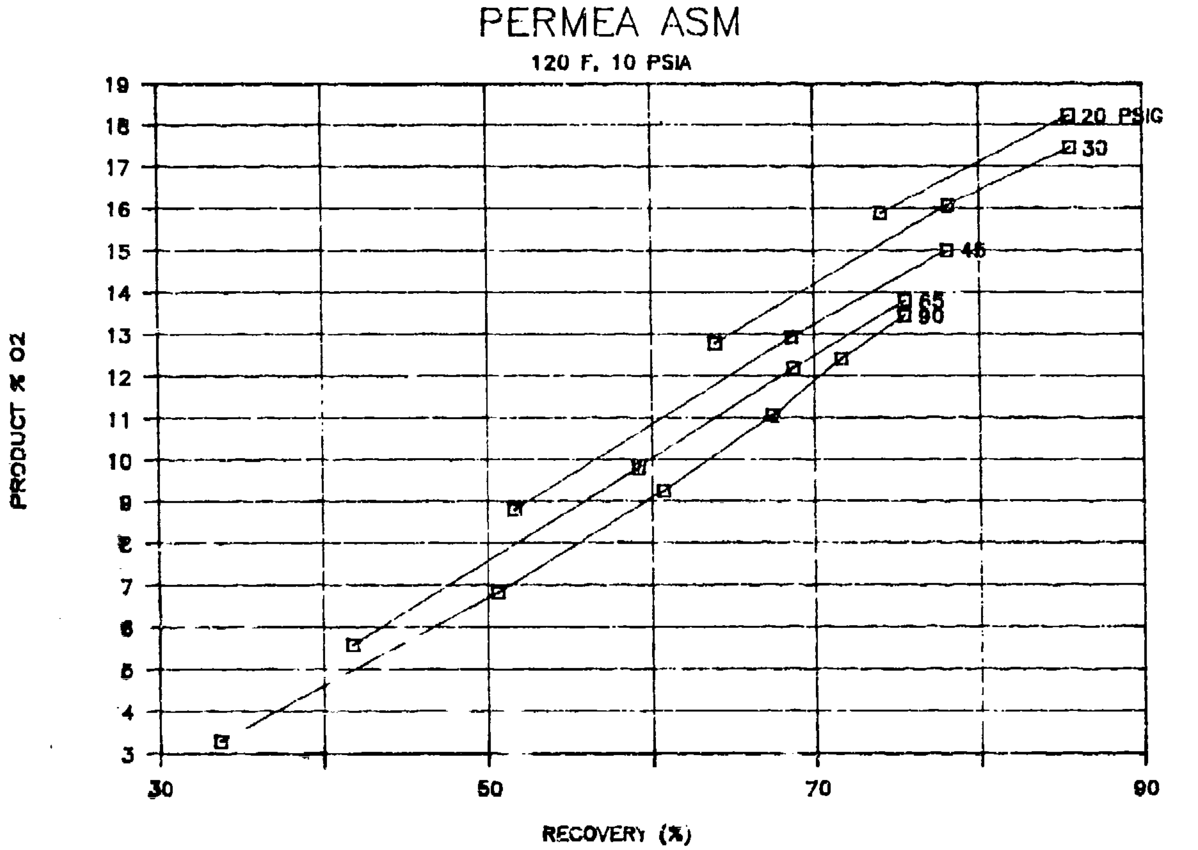


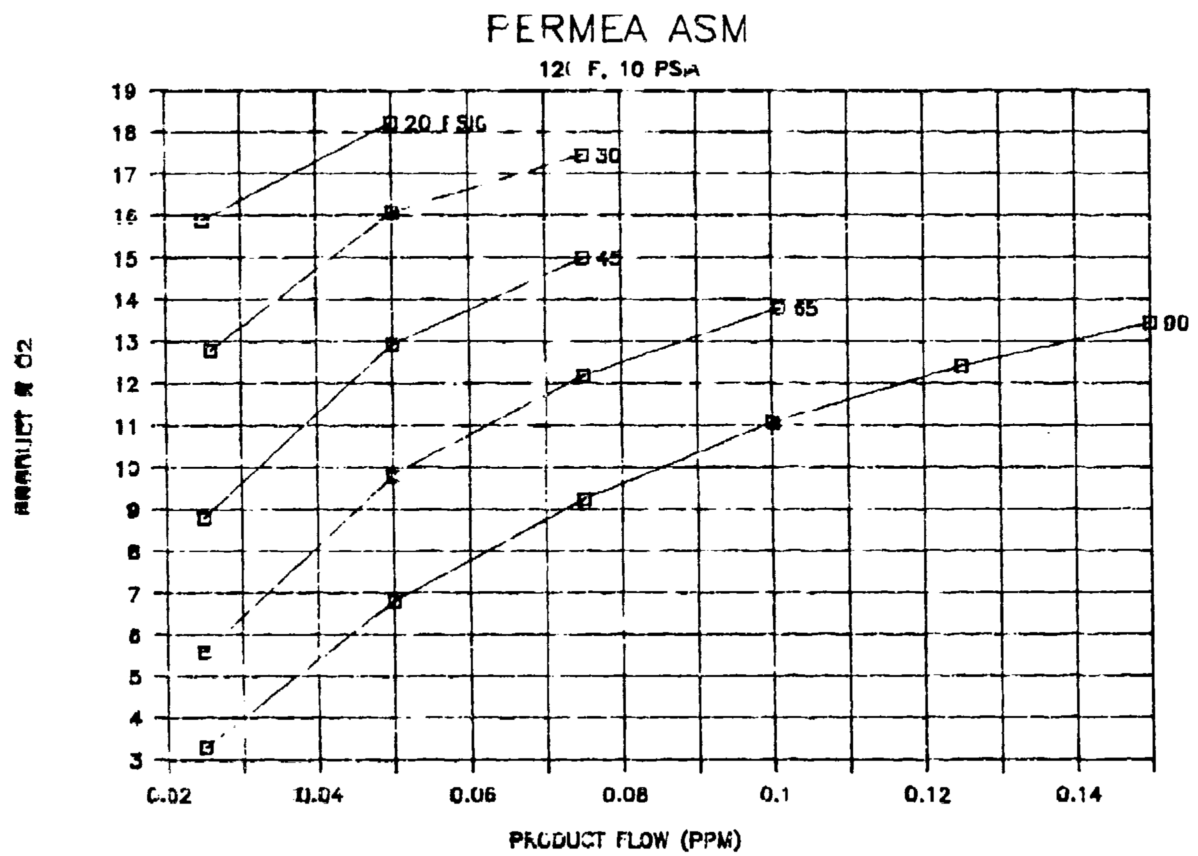
PERMEA ASM

120 F, 14.7 PSIA



APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

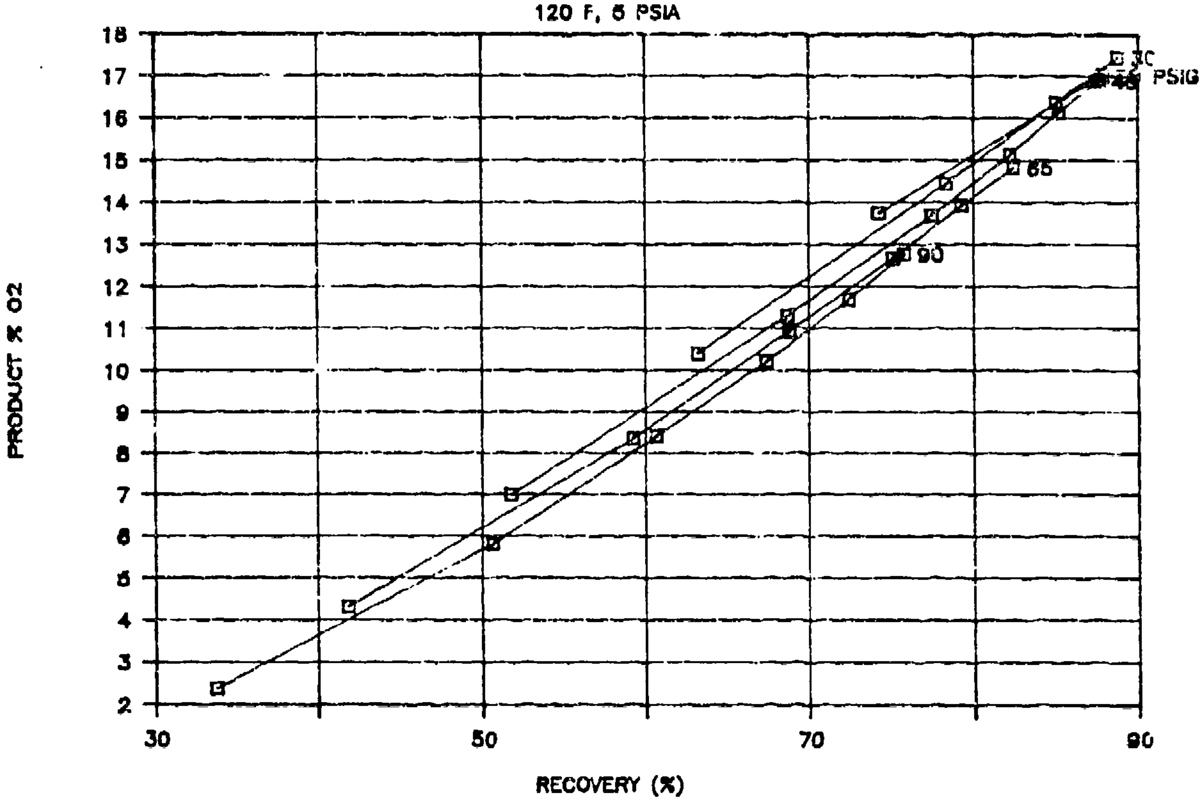




APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA

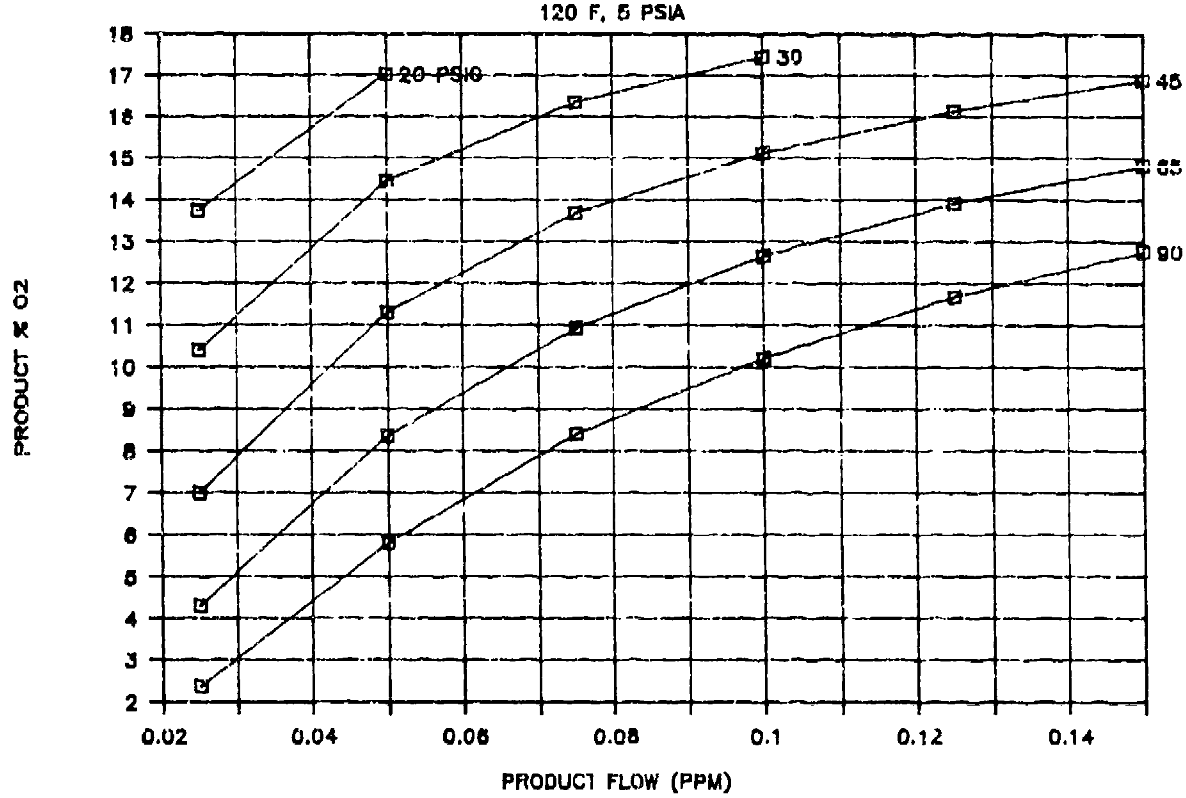
PERMEA ASM

120 F, 5 PSIA

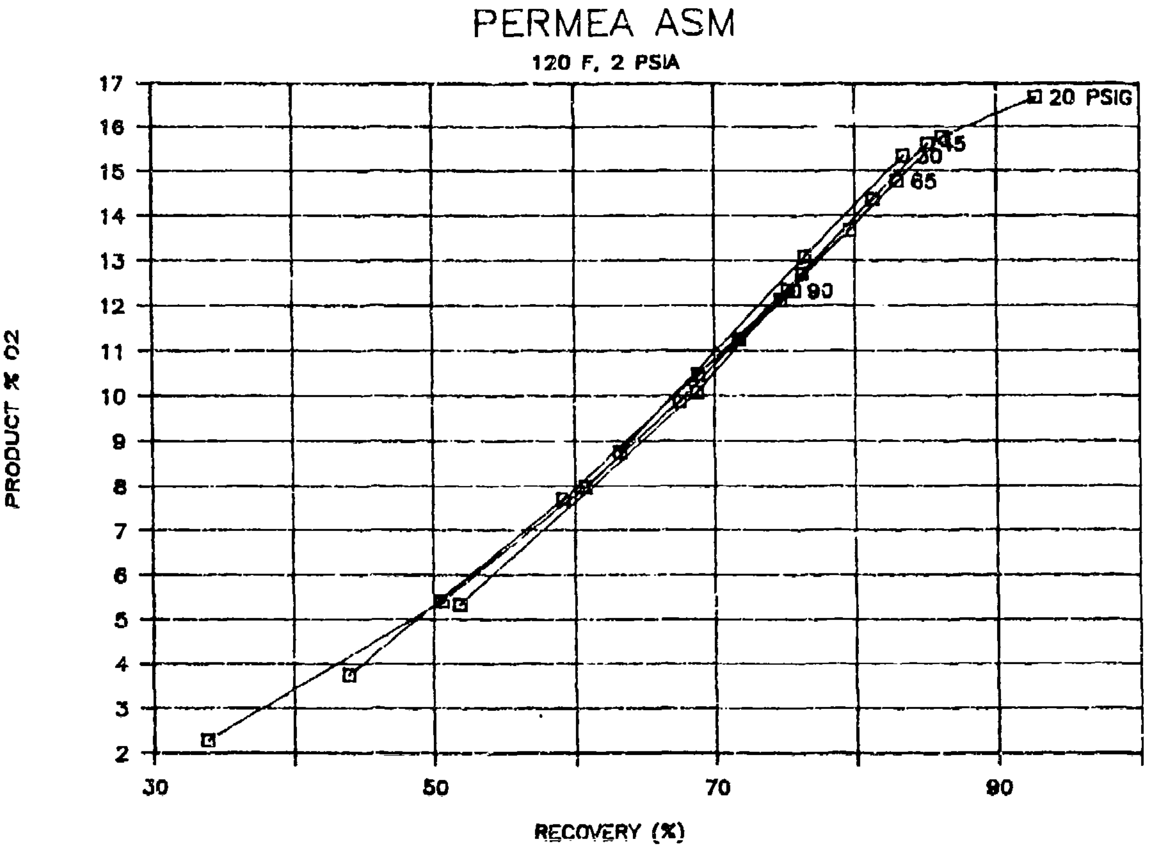


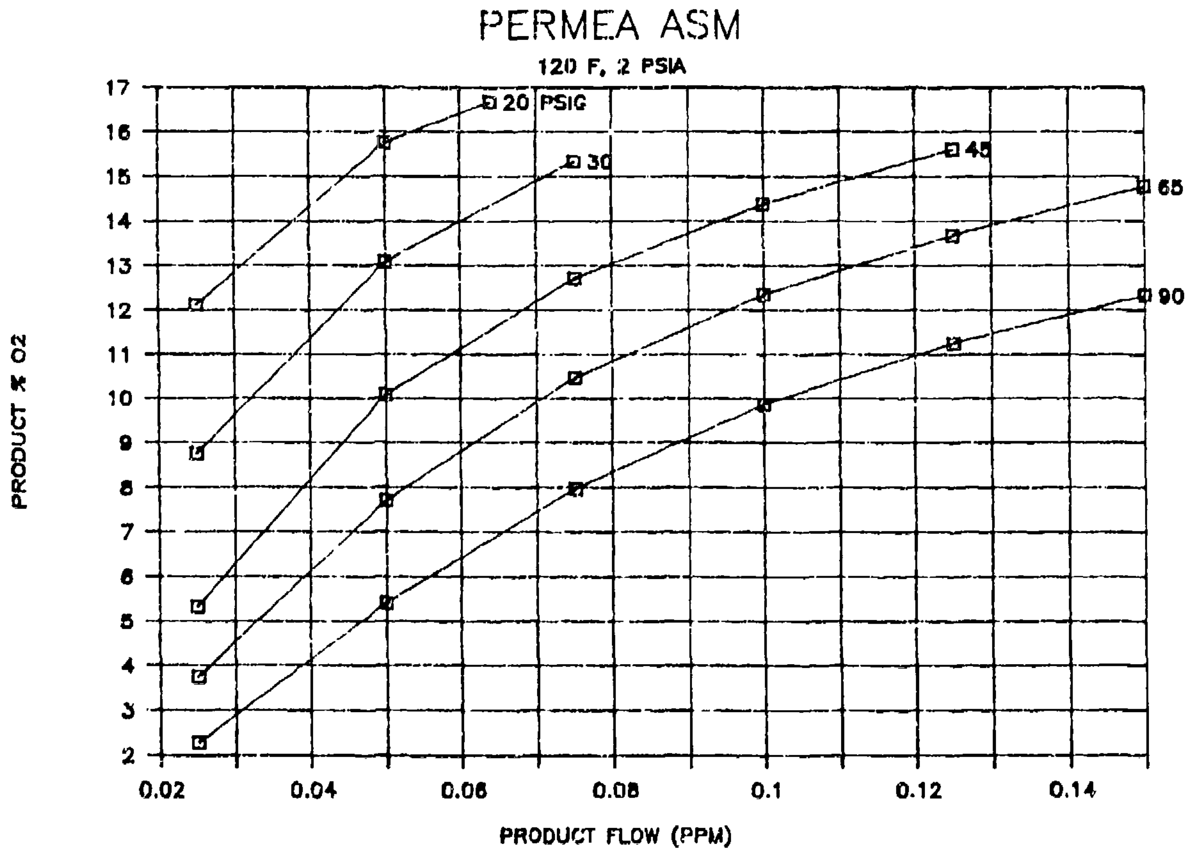
PERMEA ASM

120 F, 5 PSIA



APPENDIX E
PERMEA PERFORMANCE ENVELOPE DATA





APPENDIX F - Permea Waste Flow Model

During the Permea performance envelope testing, inlet flow was sometimes too low to be measured with the inlet flow meter. When this occurred, data was recorded as zero flow and is shown as NA (Not Available) in the tabular data. Unfortunately this occurred for a large portion of the recorded data points. In order to prepare meaningful plots of recovery versus $\%O_2$, a reasonably accurate method of estimating waste flow (and then calculating recovery) was devised.

The waste flow for any membrane based ASM will be a strong function of the average pressure difference across the fiber wall. This pressure difference was directly measured during these tests at the inlet to the ASM. Compensating for half of the pressure drop down the bore of the fiber will yield the average differential pressure. With these relationships in mind, the following model was derived:

$$W_{waste} = A \times P_{psig} + B \times (W/P_{psia}) + C$$

where P_{psig} = ASM inlet pressure referenced to waste, PSIG.
P_{psia} = ASM inlet absolute pressure, PSIA.
W = Product flow rate, PPM.

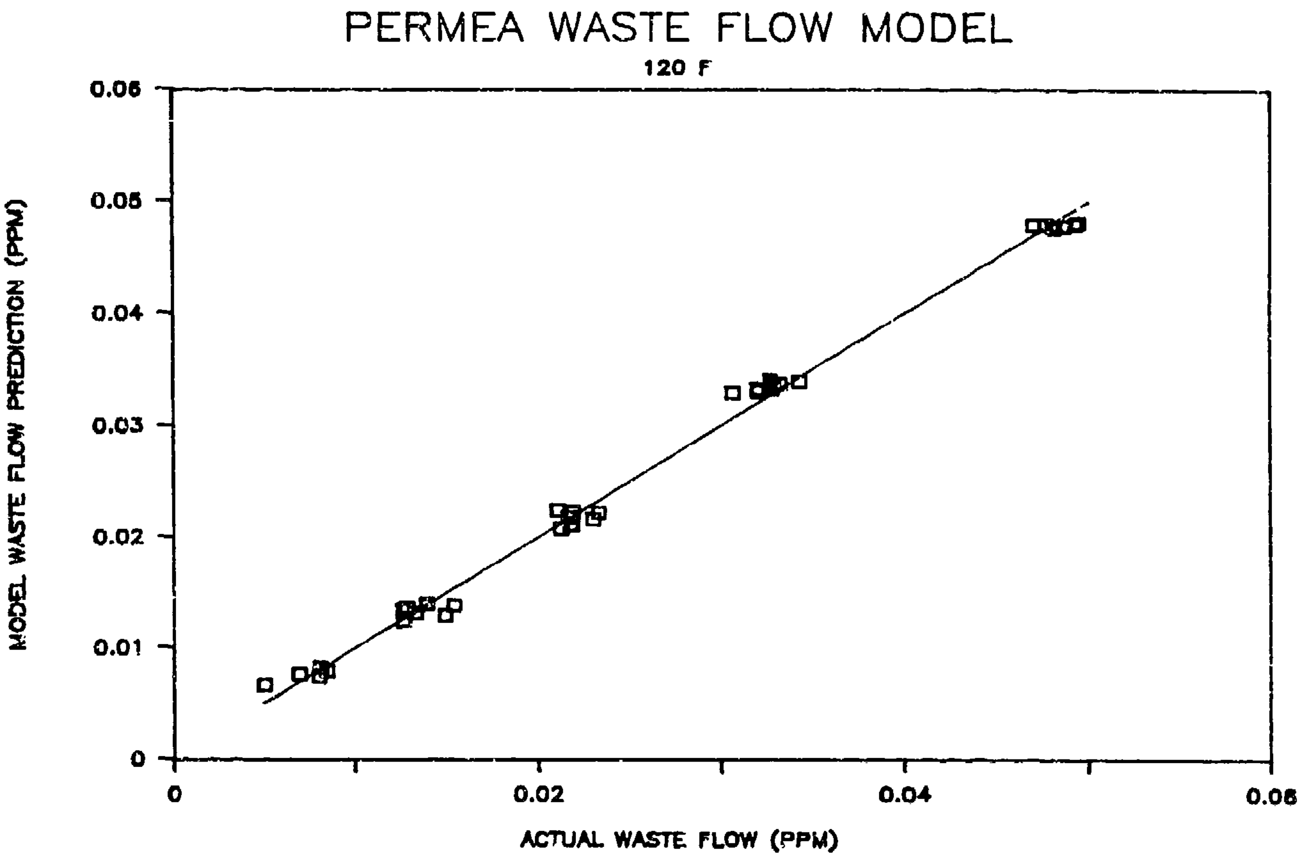
and

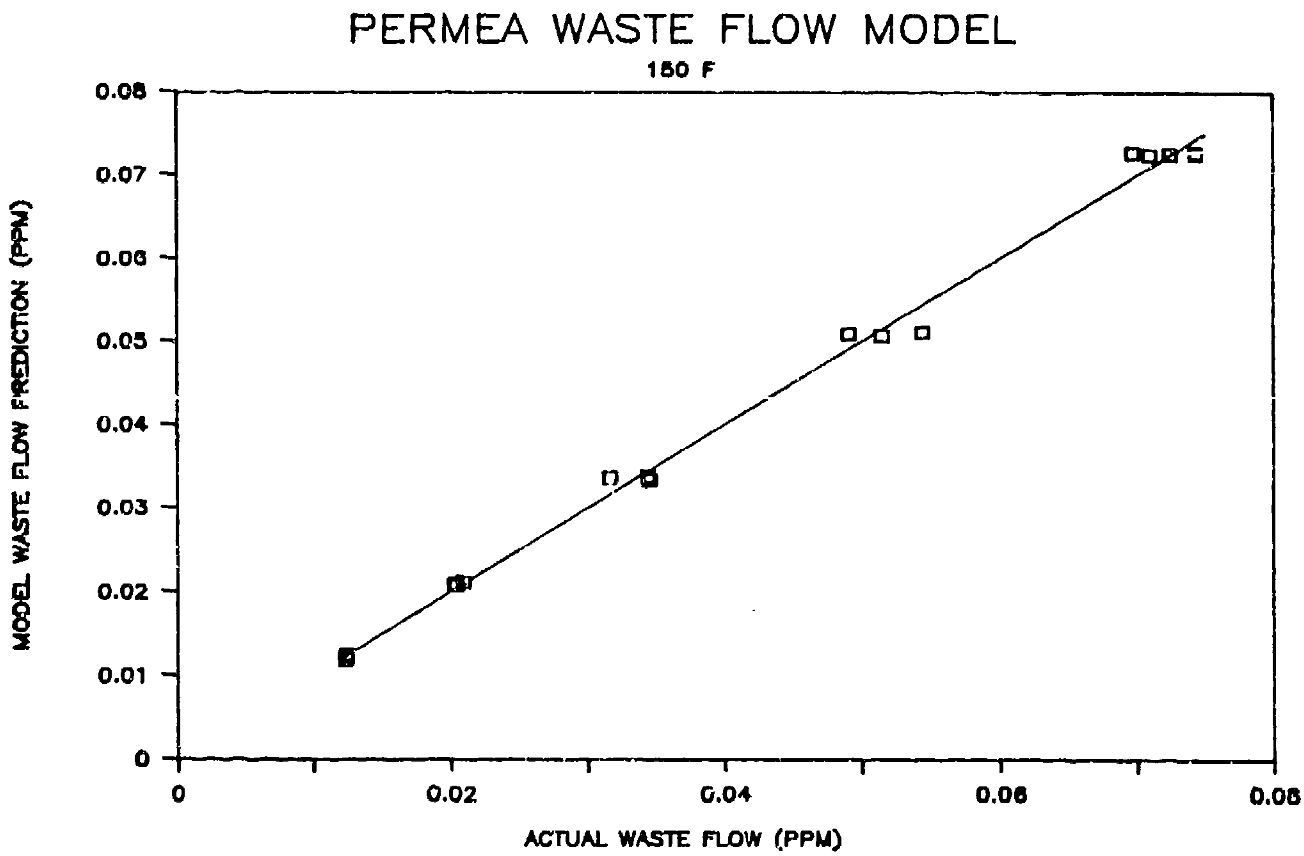
		@120°F	@150°F	@175°F	@200°F
A	=	0.0005675	0.0008676	0.00117	0.001526
B	=	-1.03049	0.75362	0.57262	1.68704
C	=	-0.0017	-0.0064	-0.0054	-0.01131

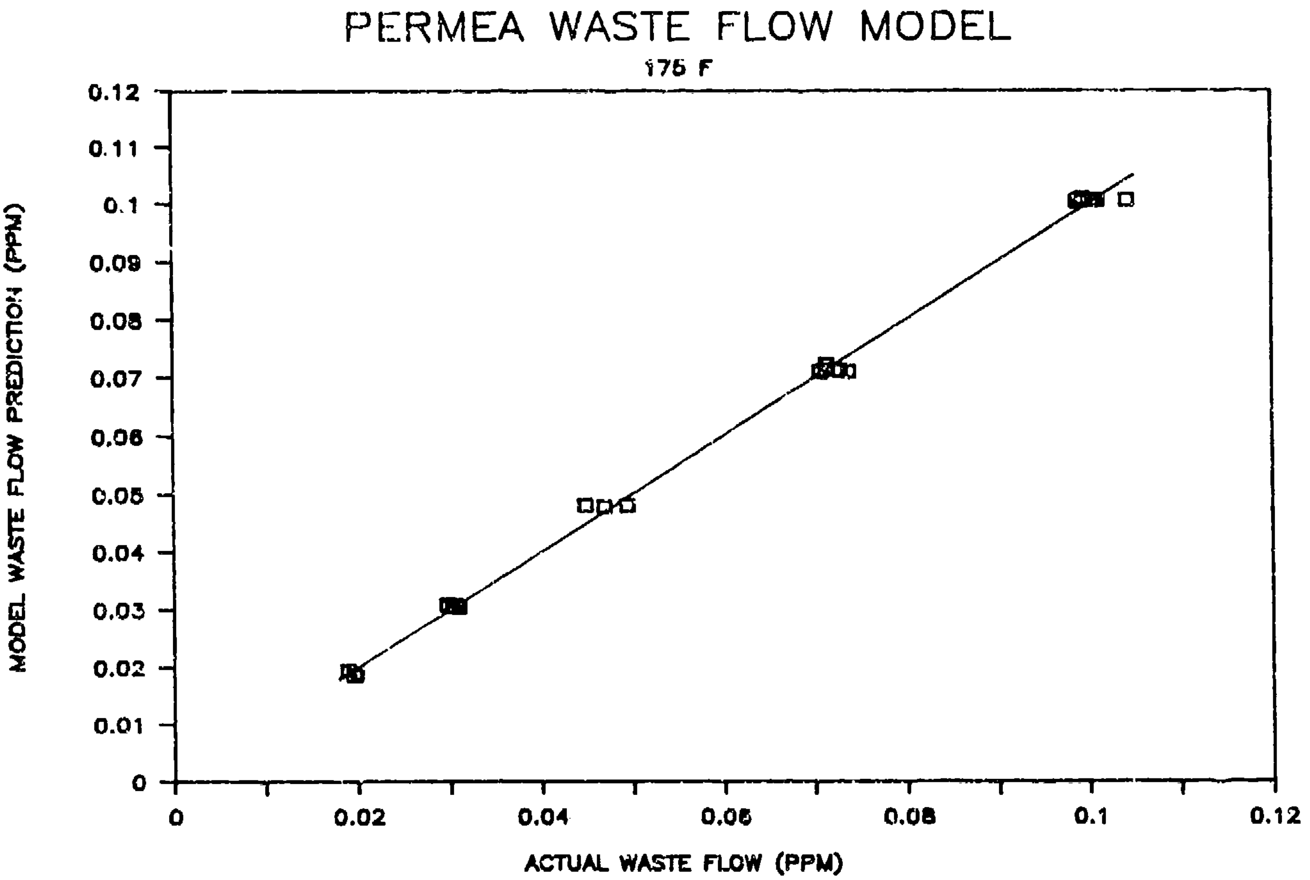
Once waste flow is known, inlet flow and recovery can be calculated from product flow as follows:

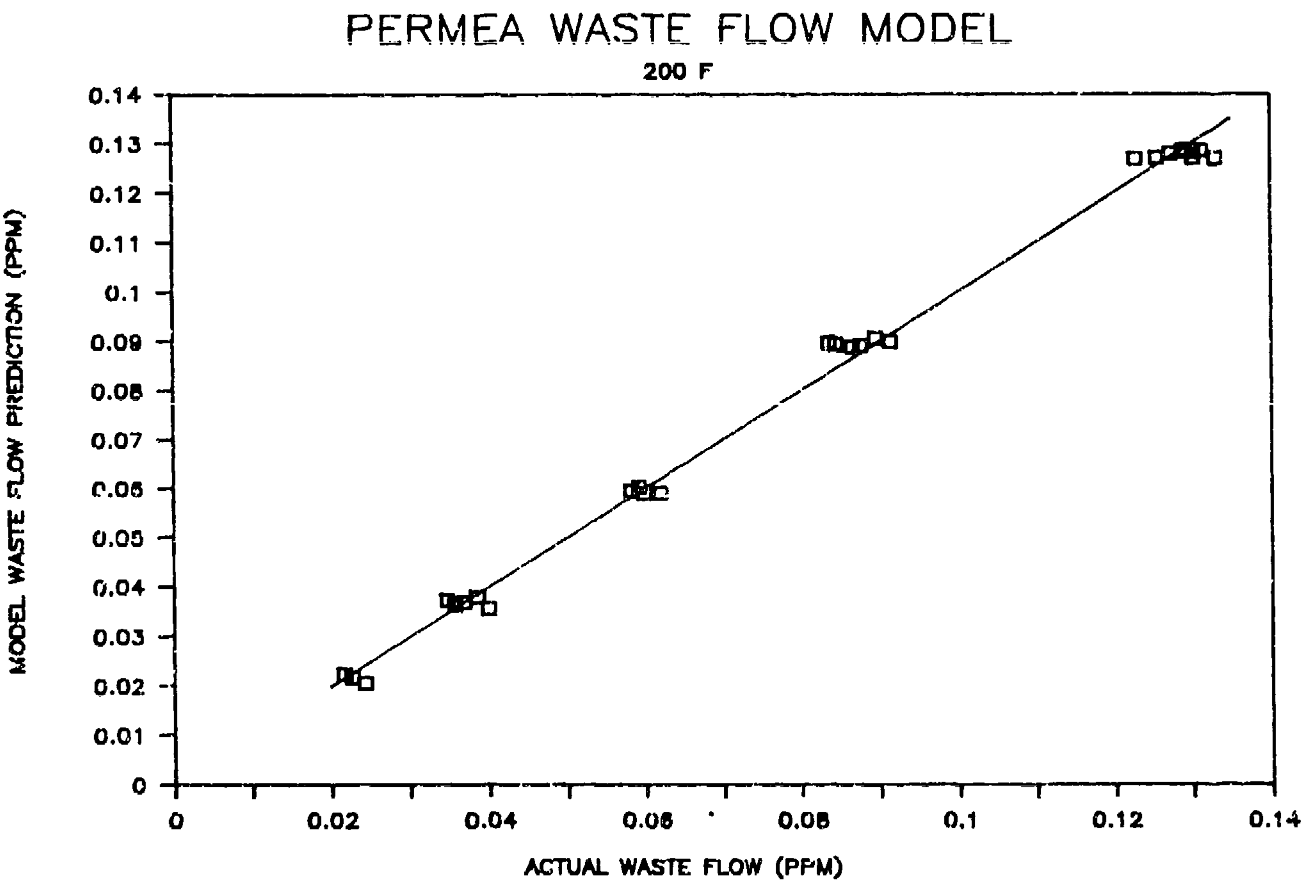
$$\text{Recovery} = \frac{W_{prod}}{W_{prod} + W_{waste}} \times 100$$

The accuracy of this model is demonstrated on the following pages for conditions where recovery could be measured. This model proved to be completely adequate for predicting recovery at the operating points where inlet flow was too low to be metered.


PERMEA WASTE FLOW MODEL
120 F
MODEL WASTE FLOW PREDICTION (PPM)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
ACTUAL WASTE FLOW (PPM)


PERMEA WASTE FLOW MODEL
150 F
MODEL WASTE FLOW PREDICTION (PPM)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08
ACTUAL WASTE FLOW (PPM)


PERMEA WASTE FLOW MODEL
175 F
MODEL WASTE FLOW PREDICTION (PPM)
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08
0.1
0.12
ACTUAL WASTE FLOW (PPM)


PERMEA WASTE FLOW MODEL
200 F
MODEL WASTE FLOW PREDICTION (PPM)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
ACTUAL WASTE FLOW (PPM)

APPENDIX G - Inlet Air Contamination

Since the A/G ASM exhibited a sensitivity to inlet air contamination in the form of synthetic oil vapor, it is of interest to compare the test air contamination with the contamination that might be expected in the bleed air of actual military airplanes. Reference 1 provides a thorough treatise on bleed air contaminants, including particulates, liquids (aerosols), and vapors.

Regards particulates and aerosols, these must be completely filtered since the membranes will be most probably be plugged or coated by anything other than gases. It is not reasonable to expect an ASM to operate with these inlet air contaminants present. In short, good high efficiency filters must be assumed on the inlet to all membrane ASMs. These filters are also discussed in some detail in Reference 1 and should not impose significant weight penalties.

A normal airplane environment may include exposure to hydrocarbon vapors from oil, combustion products and fuel vapor. Of these, oil vapor from vaporized and/or thermally degraded engine oil is considered the most probable source of vapor contaminants. Oil is usually introduced into the compressor section of the engine via oil seal leaks and subsequently converted to vapor. Compressor temperatures can easily exceed 1000°F in modern high performance engines.

One scenario for oil leaks is that of seepage past the seals while the engine is not operating (standing overnight for example). On each engine start, a "slug" of oil vapor will be introduced in the bleed air system. This could occur on a regular basis without signaling a problem to maintenance personnel. Another oil leak scenario involves admittedly infrequent but relatively major oil leaks during flight. An oil leak large enough to introduce significant quantities of oil vapor into the bleed system could occur infrequently for short periods of time (before the flight can be ended and repairs made). However, it is probably unacceptable to allow this type of engine malfunction scenario, regardless of how infrequent, to damage the ASM.

From research into contaminant levels considered acceptable from the current engine specification standpoint, it is interesting to note that the maximum allowable limit for oil breakdown products is 1.0 part per million (Table G-1).

Note in Table G-1 that the hydrocarbon concentrations during a sever oil leak test were over 100 parts per million. Considering the magnitude of this oil leak (0.5 GPM) this concentration is surprisingly low and is primarily achieved through the use of center bleed extraction points (expected on all modern engines). Engine manufacturers indicate that hydrocarbons of any type will not be measurable (less than 0.5 parts per million) in the bleed air of properly maintained modern engines (excepting start-up).

Table G-1. Comparison of Bleed Air Contaminants

Substance	Allowable Limit as per MIL-E-5007D (PPM)	Measured in CFM-56 Oil Leak Test (Reference 10) (PPM)	**Advanced ASM Performance Evaluation** (PPM)
Carbon Dioxide	5000.0	320	Ambient
Carbon Monoxide	50.0	37	-
Ethanol	1000.0	ND*	-
Fluorine (as HF)	0.1	Not Measured	-
Hydrogen Peroxide	1.0	0.5	-
Aviation Fuels	250.0	2.0	-
Methyl Alcohol	200.0	ND*	-
Methyl Bromide	20.0	ND*	-
Nitrogen Oxides	5.0	1.3	-
Acrolein	0.1	0.7	-
Oil Breakdown Products	1.0	ND*	-
Ozone	0.1	ND*	-
Hydrocarbons (Lube Oil, hydraulic fluid, cleaning fluids)	Not Listed	122.0	3/9**
Glycol	Not Listed	Not Tested	-

*ND - Non-detected (less than 0.5 PPM)
**With/Without Carbon Filter
PPM - Parts per million

Engine manufacturers typically use Flame Ionization Detectors (FID) to measure total hydrocarbons in bleed air. This device essentially counts carbon-hydrogen bonds. The analyzer is not specific and is usually calibrated on methane with measured concentrations given as methane equivalent.

The presence of a detectable odor in the air supply and on the ASM itself prompted an investigation of the inlet air contamination during these tests. The source of the odor was found to be thermal degradation products of the synthetic compressor lubricating oil used in the supply air compressor (Anderol 750). Prior to this investigation, the air supply was considered to be "clean" and essentially free of any contamination due to the low vapor pressure synthetic lubricant used in the air compressor and the high quality multi-stage particulate/coalescer filters located on the compressor outlet and ASM inlet. This oil was an ester based synthetic lubricant (similar to the MIL 7808 engine oil used in military airplanes) with no detectable odor and an extremely low vapor pressure (10^{-5} mm Hg at room temperature, virgin oil). This vapor pressure equates to a theoretical concentration of 0.1 parts per billion in the air supply. However, the small quantity of oil that migrates past the piston rings of the compressor is apparently undergoing thermal degradation at the temperatures encountered in the compression chamber (estimated at 350°F or higher). The small quantity of liquid oil which is extracted with the condensate from the compressor discharge air has the same characteristic odor as that detected on the ASM.

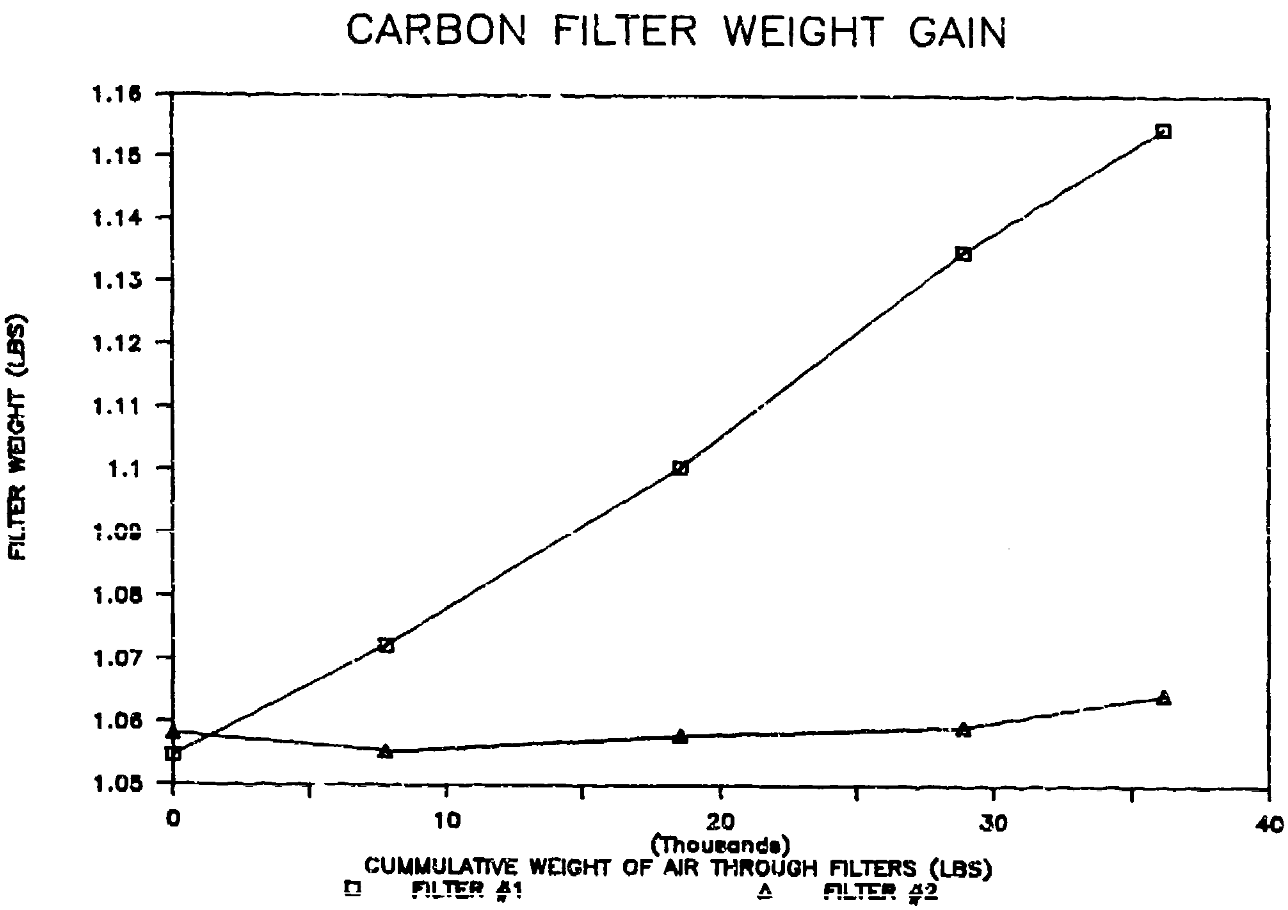
There were four methods used to ascertain the levels of test air contamination:

- o Smell
- o Carbon filter weight gain
- o FID
- o Gas Chromatograph/Mass Spectrometer (GC/MS)

When the carbon filters were installed on the inlet to the ASM, no odor could be detected downstream of the filters whereas a definite strong odor was present upstream. While the air downstream of the carbon filter was odor free, it could have still contained slight amounts of the upstream contaminants either below the detection threshold or odorless.

During the endurance testing, the carbon filters were periodically weighed and found to increase in weight as a direct linear function of total mass of air passing through the filters. Using delta weight divided by the cumulative mass of air passed through the filter, an approximation of inlet air contamination could be calculated assuming that the carbon filters were removing most of the

the contaminants. These calculations yielded a rough average concentration of 3 parts per million by mass. The following chart shows the weights of both filters versus cummulative mass of air through the filters. Note that the first filter removed virtually all contaminants that could be absorbed by the carbon since the second filter did not show any significant weight gain.



An FID was used to quantify hydrocarbon levels in and out of the carbon filters. A Beckman Model 402 FID was calibrated on methane and used according to ARP 1256A with the following results:

Sample Location	Average Concentration (Parts per million as CH_4)
Filter #1 Inlet	9.3
Filter #2 Inlet	3.1
Filter #2 Outlet	2.8

Note that the first carbon filter removed the vast majority of what it was capable of adsorbing since little difference was seen between the outlet concentration of the two carbon filters. This also confirms the filter weight data. Since the analyzer is not specific, the remaining nominal 3 parts per million that was still entering the ASM could not be identified but is suspected to be lower molecular weight hydrocarbons. The carbon filter manufacturer specifies that most C_3 and lighter hydrocarbons will not be adsorbed by the carbon. The vapor adsorption performance of the carbon filter is described by the manufacturer as follows:

Good To Excellent Adsorption	Little or No Adsorption
Most C_4 and heavier hydrocarbons	Carbon Monoxide
Ketones	Carbon Dioxide
Alcohols	Amines
Esters	Ammonia
Ethers	Acetylene
Organic acids	Most C_3 and lighter hydrocarbons
Chlorinated organics	Sulfur Dioxide
Freons	
All aromatic hydrocarbons	
Carbon disulfide	

Attempts to further identify the exact nature of the inlet air contaminants using GC/MS analysis produced results in marked conflict with the above data. The GC/MS analysis reported contaminants totaling less than 1 Part Per Billion and identified them as halogenated solvents. This data is considered to be flawed due to its disagreement with the less specific but high confidence FID and carbon weight gain data.

APPENDIX H - Bleed Air System Weight Penalty Models

In order to evaluate airplane weight penalties associated with bleed air usage, the equipment weights required to deliver and cool the bleed air must be estimated. This task becomes complicated by the fact that bleed air systems can vary widely between types of airplanes. In an attempt to develop meaningful weight estimates, bleed air delivery and cooling systems of several different sizes were designed and empirical models developed to approximate their weights. Two different types of airplanes were used for this analysis, an ATF (sustained supersonic fighter) and a subsonic transport. It was felt that the supersonic fighter would represent the highest bleed cooling penalties and the transport the least due to the inherent difficulties rejecting heat in a supersonic airplane with high stagnation air temperatures.

Generic ATF

Using the weight estimates originally developed in Reference 9 for a generic ATF design, a weight model was derived that would account for varying bleed flow and ASM inlet temperatures (Figure H-1 and H-2). Note that there are two versions of the system design based on the need for further cooling below 170°F. The empirical weight models for individual components are listed below.

Weights Applicable to Either Temperature System

$$\text{Pre-Cooler Growth} = e^{(0.78\,Ln(W+15) + 0.3632)} - 11.87$$

$$\text{Bleed Duct Growth} = e^{(0.81\,Ln(W+15) + 0.9339)} - 22.81$$

$$\text{OBIGGS Supply Duct} = e^{(0.484\,Ln(W) - 0.0713)}$$

where W = Bleed Air Flow Rate, Lbs/Min

Weights for OBIGGS Operating Below 170°F

$$\text{Primary HX Growth} = e^{(0.75\,Ln(W+15) + 0.2097)} - 9.4$$

$$\text{Secondary HX} = [e^{0.65\mathrm{Ln}(W) + 0.8905}] \times [(170 - T)/75]^{0.66}$$

$$\text{ECS Growth} = [e^{(0.794\mathrm{Ln}(W) + 0.9512)}] \times [(170 - T)/75]^{0.66}$$

where T = OBIGGS Inlet Temp, ^{o}F
(<u>less than</u> $170^{o}F$)

<u>Weights for OBIGGS Operating Above $170^{o}F$</u>

$$\text{Primary HX Growth} = [e^{(0.75\mathrm{Ln}(W+15) + 0.2097)} - 9.4] \times [(450 - T)/280]^{0.66}$$

where T = OBIGGS Inlet Temp, ^{o}F
(<u>greater than</u> $170^{o}F$)

Secondary HX = 0

ECS Growth = 0

<u>Generic Transport</u>

The weight estimates shown in Figure H-4 are based on a hypothetical baseline transport type airplane (Boeing C-X). An OBIGGS bleed air delivery system configured as shown in Figure H-3 was chosen for its simplicity and dependence on low stagnation temperature ram air for heat rejection. The ram air heat exchanger was designed for operation at altitude.

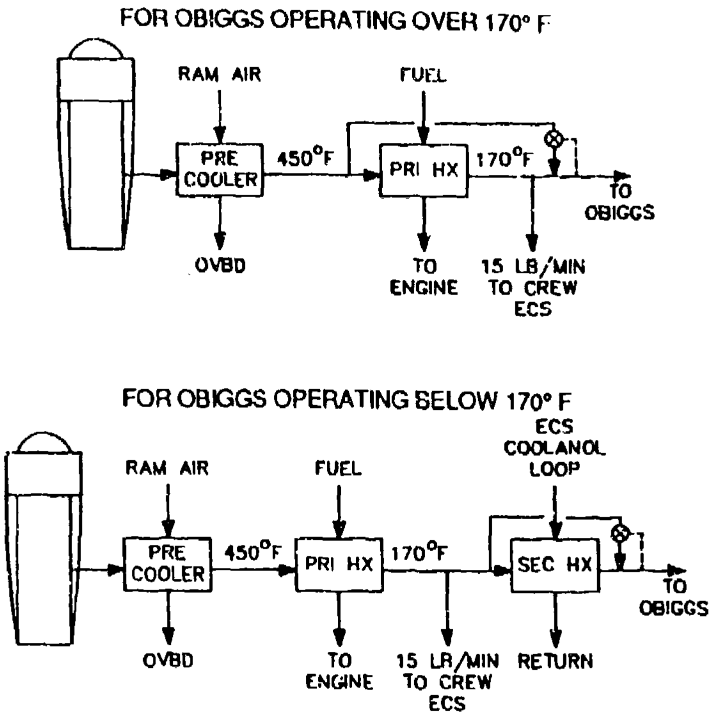


Figure H-1. Schematic of OBIGGS Bleed Air Supply for Generic ATF

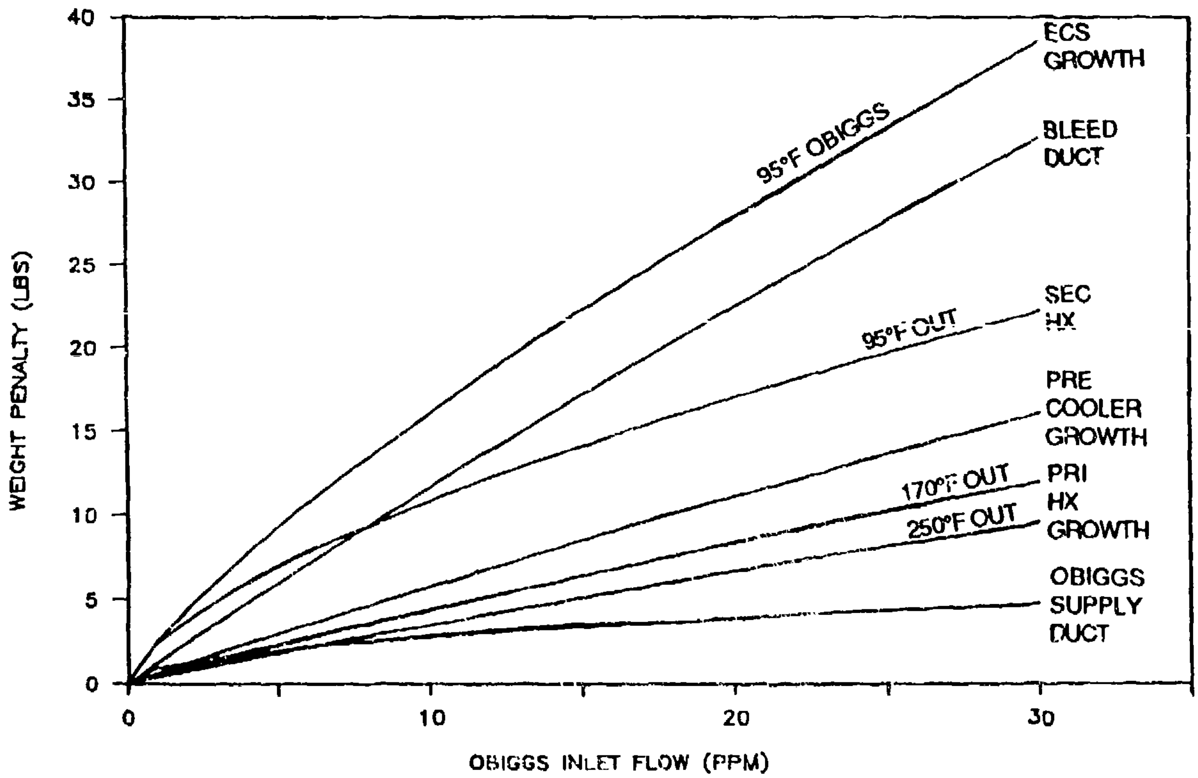


Figure H-2. Estimated Bleed System Weight Penalties for Generic ATF

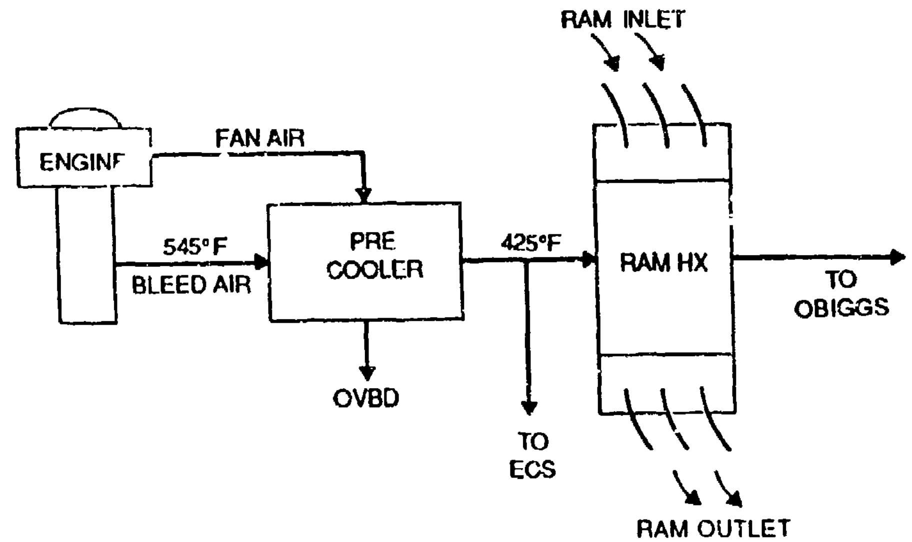
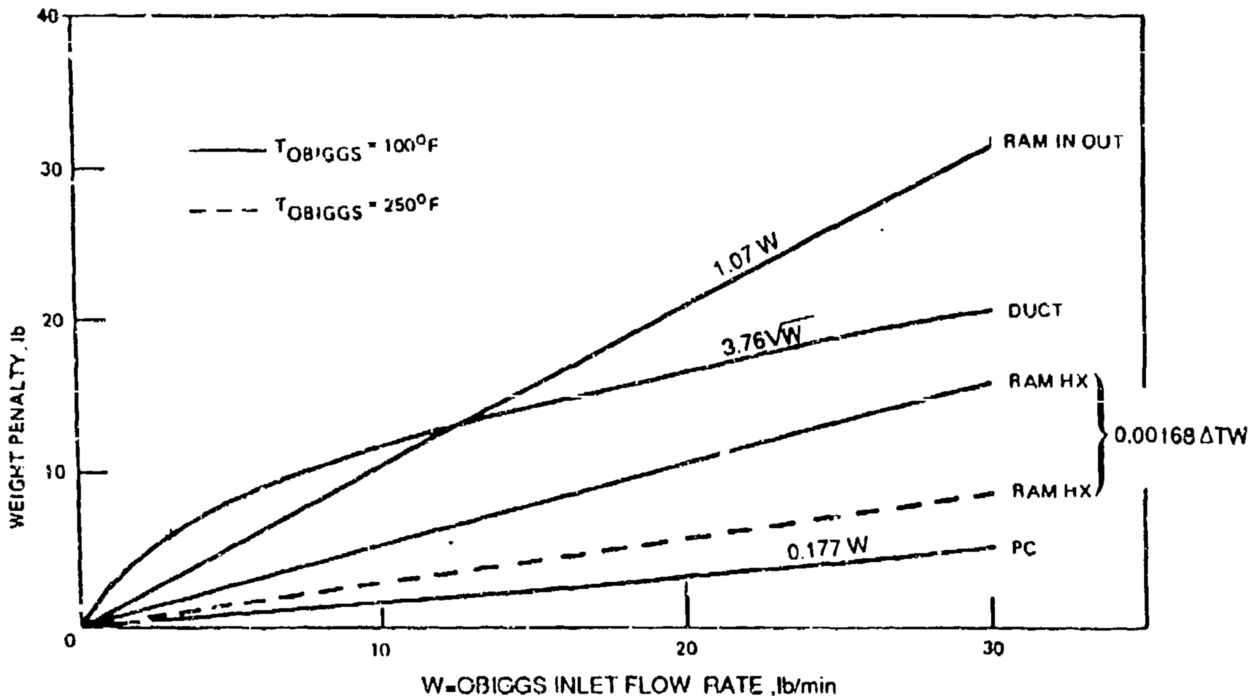


Figure H-3 Schematic of OBIGGS Bleed Air Supply for Generic Transport



PC = Precooler Growth
RAM HX = Ram Air Heat Exchanger
DUCT = Ducting to OBIGGS
RAM IN OUT = Ram Air Inlet
ΔT = 425-T°F

Figure H-4. Estimated Penalties for Generic Transport

APPENDIX I - Permea Final Report

ADVANCED AIR SEPARATION SYSTEMS FOR OBIGGS APPLICATIONS

Prepared by:

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A Monsanto Company
St. Louis, Missouri

and

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San Diego, California

for the

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Aero Propulsion Laboratory
Wright Patterson Air Force Base
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February 5, 1988

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1.0 Introduction

For the past several years, Sunstrand Pneumatic Systems and Permea have been actively developing hardware to introduce inert gas generation equipment onboard aircraft for the purpose of fuel tank inerting. With recent technology advances by Permea in the development of a highly efficient, durable air separation membrane, it can now be shown that an OBIGGS unit incorporating this technology provides the lowest life cycle cost alternative when compared with technologies such as reticulated foam, stored liquid nitrogen or molecular sieves. In addition, this system in most cases will offer the lowest aircraft weight penalties and bleed air requirements for both the on demand and stored gas OBIGGS unit.

Permea, a Monsanto Company, is the world's largest supplier of membrane gas separation equipment with more than 250 systems operating worldwide. More than 100 of these systems are used for the separation of air for nitrogen production. The hollow fiber membrane manufactured by Permea has both high temperature and high pressure capabilities and is produced in 2", 3", 4", 6" and 8" diameter units. The membranes have demonstrated excellent efficiency and reliability in critical industrial applications.

In order to provide the aircraft manufacturer with a complete onboard inert gas generating system, Permea joined forces with Sundstrand Pneumatic Systems (SPS) in San Diego, California. SPS has provided sophisticated aerospace products for many years which in many cases has involved integration of a multitude of technologies. With SPS's capability to design high pressure compressors, pressure regulators, controllers, heat exchangers and fans along with Permea's ability to produce advanced hollow fiber membranes, we are able to offer the complete OBIGGS unit.

2.0 Permea ASM

2.1 ASM Description

The ASM supplied to BMAC on a loan basis was produced at Permea's manufacturing facility in St. Louis, MO. The ASM was a single PRISM Alpha separator which was a nominal 2" diameter and 30" long. This particular separator was designed for high pressure industrial use. The suggested operating envelope for this unit is shown by the shaded region in Figure 1. The general specifications are shown below.

General Specifications

Overall ASM Length	: 30 in.
Overall ASM Diameter (OD)	: 2.4 in.
Overall ASM Weight	: 3.6 lbs.
Active Fiber Length	: 20.5 in.
Fiber Weight	: 0.4 lbs.
Tube Sheet Weight	: 0.7 lbs.
Case Material	: Fiberglass
Tubesheet Retainer	: 0.5 lbs.

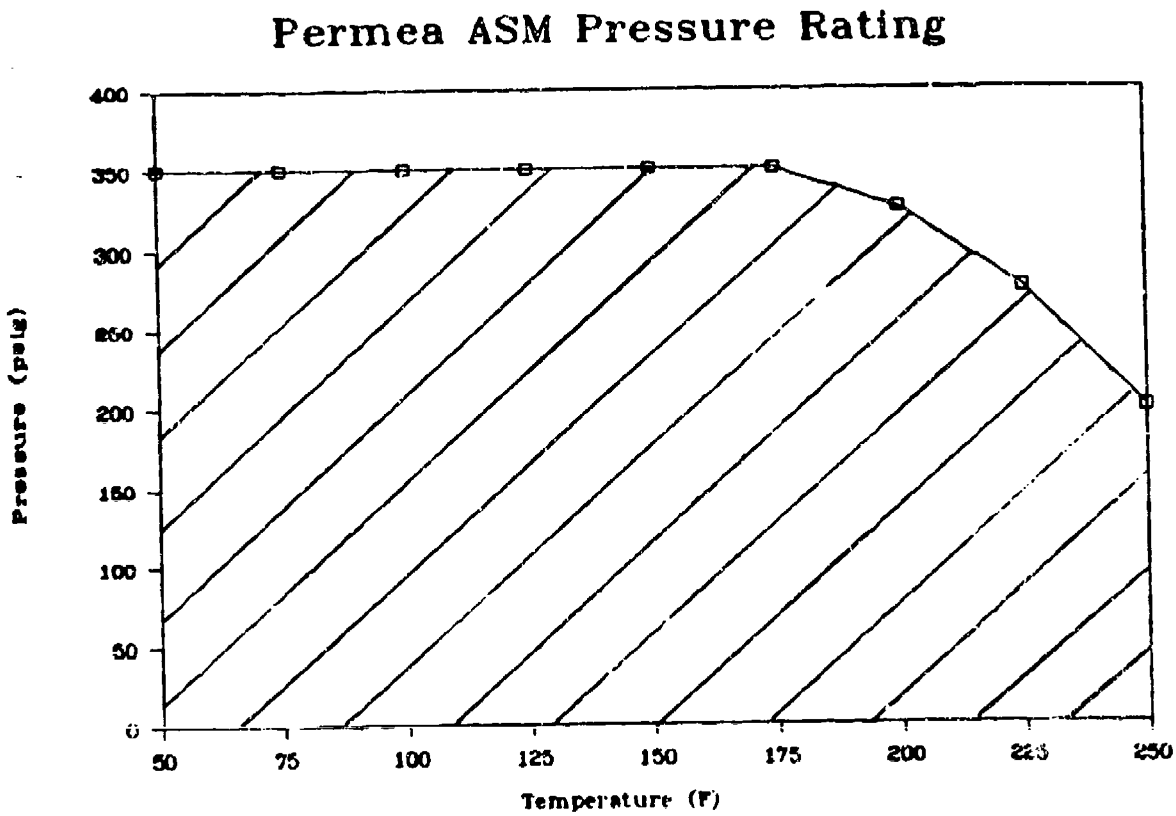

FIGURE 1

Because the unit was designed for high pressure operation, the materials required for the tubesheet and casing were considerably heavier than that required for the low pressures used during the test. No attempt was made to minimize the weight since the separator was provided on a loan basis. Given that the maximum pressure of the test was 80 psig, significant reductions in the weight are possible. Also, to produce higher flowrates, larger diameter ASMs would be employed to save weight and to avoid the complications of multiple small diameter units. It is sometimes very difficult to establish equal flowrates to multiple units particularly when the total flowrate and pressure may be changing as is the case as an aircraft goes through various missions.

2.2 Principle of Operation

PRISM Alpha semipermeable membranes employ the principle of selective permeation to separate gases. Each gas has a characteristic permeation rate which is a function the its ability to dissolve and diffuse across the membrane wall. If a gas, such as oxygen and water, has a high solubility and diffusivity, it will permeate across the membrane rapidly and is termed a 'fast' gas. Other gases, such as nitrogen, are not as soluble nor do they diffuse as rapidly. As a consequence, nitrogen permeates more slowly and is referred to as a 'slow' gas. The difference in permeation rates allows the fast gas (oxygen and water) to be separated from the slower gases (nitrogen and argon).

PRISM Alpha separators are bundles of these semipermeable membranes formed into hollow fibers. Hollow fibers are the most effective way of providing high membrane area per unit volume. Thousands of these hollow fibers in each separator provide maximum separation area in a compact, lightweight, easily handled module. The hollow fiber bundle is encased at each end by a tubesheet. The bleed air is fed to one end of the tubesheet and introduced to the boreside of the hollow fibers. As the air travels the length of the fibers, the oxygen and water are removed preferentially across the fiber wall creating a dry nitrogen enriched air (NEA) stream within the fiber. The NEA stream is collected at the tubesheet opposite the feed end. The oxygen enriched stream collected on the outside of the fiber surface is vented.

2.3 Performance Characteristics

The polymer used to make PRISM Alpha separators is the thermoplastic polysulfone. This polymer has a high inherent separation capability which allows PRISM Alpha separators to produce NEA gas with high efficiency. This minimizes the quantity of bleed air required to feed the ASM and the associated conditioning of that air. The efficiency of PRISM Alpha units are unmatched by any other membrane separator.

The efficiency is not only high but can be achieved with high bleed air temperatures. The operating temperature of 250 F greatly reduces the required conditioning of the bleed air prior to introduction to the ASM.

The performance of PRISM Alpha at high temperatures is possible because polysulfone has a glass transition temperature of approximately 375 F. This transition temperature represents the point at which the polymer begins to soften and lose its rigidity and strength. No other membrane material being offered today has the thermal and mechanical strength of polysulfone. Table 1 shows these properties in comparison with the other membrane materials currently in use or envisioned for the industrial market.

The performance of the ASM is greatly enhanced by increasing the bleed air pressure to the unit. The driving force for separation in the membrane is the partial pressure difference across the membrane wall. By increasing the feed pressure, the partial pressure driving force is increased resulting in an increased rate of oxygen removal per unit area. This allows for a significant decrease in the amount of area required to perform the required separation.

2.4 Availability

The first PRISM separator was put into service in an industrial environment in 1977. Since then, over 250 systems, each consisting of several separators, have been placed in service. As a result, Permea is

TABLE 1: Polymer Properties

Property	Polysulfone	Ethyl Cellulose	poly(4methyl pentene 1)
Water Absorption (%) ASTM D-570	0.22	0.8 - 1.8	0.1 (est.)
Heat Deflection Temp. (C) ASTM D-648	174	46 - 88	58 **
Flexural Strength (1000psi) ASTM D-790	10.15	2.03-7.98	3.48-4.06
Tensile Modulus (1000psi) ASTM D-638	363	102-305	159.5-203.0
Glass Transition Temp. (C)	190	43	19 - 29 **
Percent Elongation at Failure ASTM D-638	50-100	5-40	13-22

Data taken from Polymer Handbook, 2nd Edition, 1975, J. Brandrup and E. H. Immergut, Editors, John Wiley & Sons, New York.

** Data from "Aircraft Fuel Tank Inerting System", Report AFWAL-TR-82-2115, R. L. Johnson and J. B. Gillernin, AiResearch Mfg. Co., July 1983.

the largest supplier of industrial gas separation systems in the world.

A second generation of membrane separator called PRISM Alpha was introduced in 1986 and has been in fullscale production since that time. Over 100 systems have been sold and delivered in less than a year, many times over the nearest competitor.

3.0 BMAC Test Results

3.1 Performance Testing

The data collected indicates that the Permea ASM at 200 F has a productivity of approximately five times better than older technology based on the method of calculation. The productivity can be increased to ten times better by operation at high temperatures as was verified in subsequent tests. The Permea ASM also demonstrated high efficiencies which reduce the bleed flowrate required for ASM operation.

3.2 ASM Endurance Testing

The data collected during the tests showed an initial decline in performance followed by a stabilization of rate. The rate of decline after the initial period without the carbon filter was about 3 to 4 % per 1000 hours. This information is consistent with Permea's industrial experience in dirty, oil contaminated streams. Our experience has shown that, at the low pressures used in this test, the rate of decline would be reduced to 1 to 2 % per 1000 hours with a clean air stream.

However, the initial decline observed in the endurance test is not consistent with the data collected in more than 100 operating systems. In addition, if this decline were as significant as indicated, the data collected during the performance envelope testing should have shown an indication of changing performance when in fact the data was very consistent. This decline is likely the result of an anomalous occurrence during the startup of the endurance test setup. Based on a post test examination, the most likely scenario was introduction of liquid oil into the system.

The most likely location for introduction of liquid oil was from the heater used to preheat the air prior to the ASM. The heater was located between the filter and the ASM. If any free oil had collected in the heater, the oil would have carried over into the ASM as the temperature in the heater increased. Figure 2 shows the expected performance decline at the pressure and temperature of this test. This curve is based on the operating experience of over 100 industrial systems, many of which operate at higher pressures. In addition, Figure 2 includes a projected curve for operation at 250 F.

3.3 High Temperature Tests

At the conclusion of the performance and endurance testing, Permea and BMAC agreed to conduct additional high temperature tests. We felt that these tests were necessary to determine the feasibility of operation at higher temperatures (>200 F) and to determine the margin of safety at these higher temperatures. It is important that the ASM continue to function if fluctuating or increased temperatures result during a given mission.

The data collected demonstrated that no permanent damage occurred to the ASM until temperatures greater than 280 F were reached. This suggests that operation at 250 F may be quite practical and still provide 30 F safety margin. This higher temperature operation results in a significant weight penalty reduction for the bleed cooling system. In addition, the productivity (produced NEA flowrate) increases by approximately 50% at the higher temperatures. This is a 10 fold increase over the baseline data collected with older technologies.

4.0 Post Test Evaluation

After completion of all the tests, the ASM was returned to Permea for

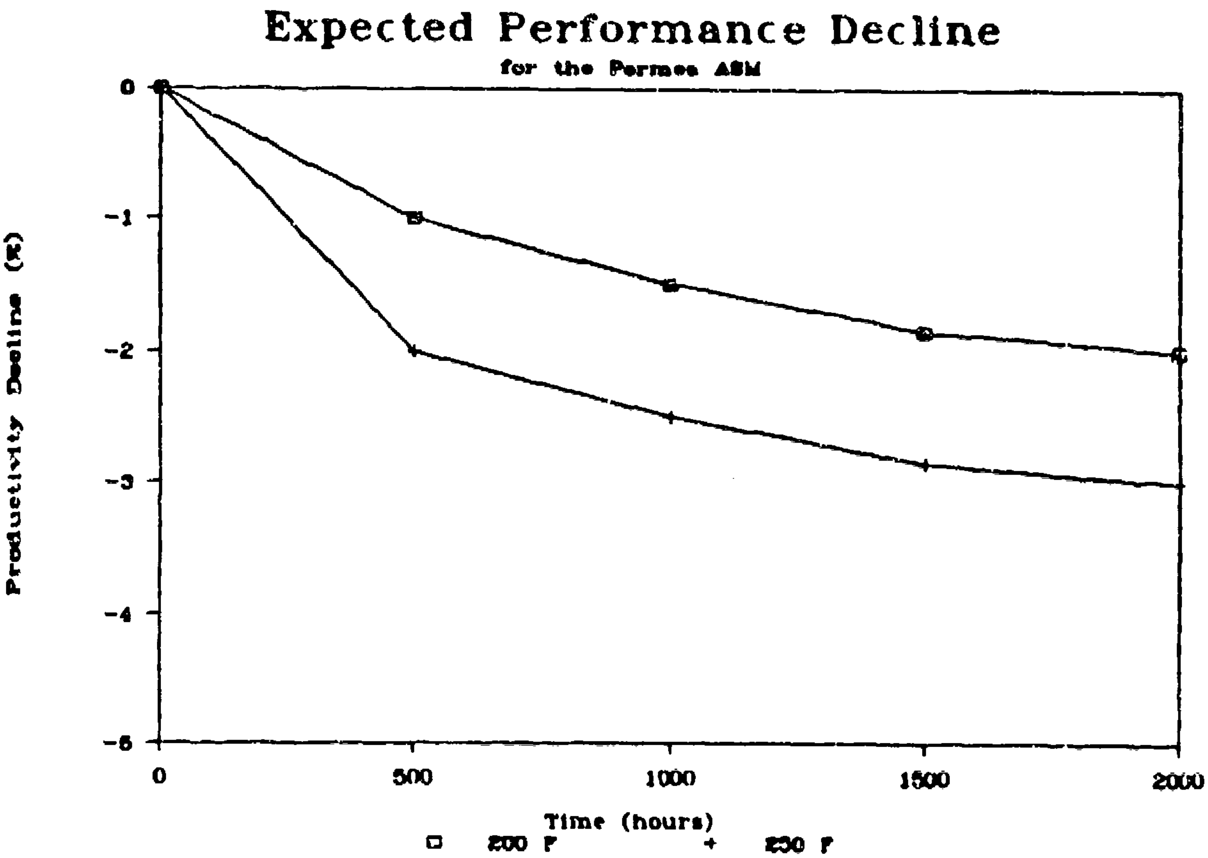

FIGURE 2

examination and analysis. Upon inspection, the ASM was found to contain a large quantity of oil on both the feed and waste side of the fiber. The quantity present was larger than typically expected for only 1000 hours of operation in the contaminated air based on the analysis of oil present in the air. This suggests that additional quantities of liquid oil were introduced at some point during the testing, possibly through the startup of the new endurance test system.

A minor shrinkage of the fiber was observed as a result of exposure to 300 F. Even at these high temperatures, there was no obvious thermal damage to the fiber. One problem observed with the high temperature operation was a degradation of the o-ring seal between the waste and feed side of the tubesheet. This problem can be corrected by changing the material of the o-ring.

After inspection, the unit was tested to obtain performance data. The unit showed a 30% decline in productivity with no change in efficiency relative to tests prior to shipment. This seemed remarkable given the high temperature operation and the quantity of oil present. An attempt was made to remove the oil with solvent treatment to measure any performance improvement. After cleaning, the productivity improved by

10 15% with no change in efficiency.

5.0 Conclusions

5.1 The Permea ASM demonstrated the ability to produce five to ten times the baseline NEA flowrate depending on the temperature of operation.

5.2 The Permea ASM showed high efficiencies over the entire range of oxygen concentrations examined. These efficiencies result in low bleed air requirements to produce a given NEA flowrate.

5.3 High temperature operation was demonstrated at 200 F and the data collected at higher temperatures suggests that operation as high as 250 F is practical. This further reduces the weight penalties associated with bleed air conditioning equipment.

5.4 As a result of the high operation temperatures and high efficiencies, the weight penalties for the Permea/Sundstrand OBIGGS unit are greatly reduced.

5.5 Permea can produce ASM diameters up to 8" in diameter. This will significantly reduce the scaleup and development expenses of the ASM.

6.0 Recommendations

6.1 Conduct further testing to verify the long term operation capability of the ASM at 250 F.

6.2 Future tests should be conducted only on full scale ASM units as proposed for actual flight conditions.

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