Development and Testing of the FAA Simplified Fuel Tank Inerting System

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ABSTRACT

Significant emphasis has been placed on fuel tank safety since the TWA Flight 800 accident in July 1996. Extensive development and analysis has illustrated that fuel tank inerting during aircraft operation could potentially be cost-effective if air separation modules (ASM) could be integrated into a system in an efficient manner. To illustrate this, the Federal Aviation Administration (FAA) developed an onboard inert gas generation system (OBIGGS) with ASMs that used aircraft bleed air to generate nitrogen-enriched air (NEA) at varying flows and purities (NEA oxygen concentration) during a commercial airplane flight cycle. The system was operated in a dual-flow methodology, as originally designed as well as a variable-flow methodology to examine the capabilities of the OBIGGS. The OBIGGS was tested on a ground test article as well as on two flying test beds. The results of initial ground testing indicated that it could be difficult to duplicate performance numbers acquired during static ASM testing. The results of OBIGGS testing on aircraft indicated that the dual-flow concept was valid and that the air separation module dynamic characteristics were as expected, given the limited scope of testing. However, bleed air consumption was greater than expected for some tests. Any deviations in system performance from test to test could be explained by the difference in warm up times before OBIGGS operation that day. The use of the variable-flow methodology did allow for a greater amount of NEA to be generated during the first part of descent to offset the potential flow of air into the vent system of an inert fuel tank.

INTRODUCTION

Background. Significant emphasis has been placed on fuel tank safety since the TWA Flight 800 accident in July 1996. The Federal Aviation Administration (FAA) has issued numerous Airworthiness Directives, enacted a comprehensive regulation to correct potential ignition sources in fuel tanks, and conducted research into methods that could eliminate or significantly reduce the exposure to flammable fuel tank vapors. Extensive development and analysis has illustrated that fuel tank inerting during aircraft operation could potentially be cost-effective if air separation modules (ASM), based on hollow-fiber membrane (HFM) technology, could be integrated into a system in an efficient manner.

The FAA, with the assistance of several aviation-oriented companies, has developed an onboard inert gas generation system (OBIGGS) with ASMs that uses aircraft bleed air to generate nitrogen-enriched air (NEA) at varying flows and purities (NEA oxygen concentration) throughout a commercial airplane flight cycle to inert a fuel tank. This system takes advantage of the operational properties of the specified ASM and a dual-flow methodology to maintain an inert ullage in a fuel tank. A variable-flow methodology was also examined.

Previous Research. Methods of inerting fuel tanks have been studied as early as the late 1940s. Macdonald and Wyeth summarized different methods of inerting fuel tanks in the 1950s, including reduction of oxygen concentration with nitrogen (ullage washing) [1]. Stored gas inerting was used by the military on various platforms in the 1970s, leading to the development of a stored gas system for an FAA-operated DC-9 commercial transport airplane. Klueg, McAdoo, and Neese evaluated this stored liquid nitrogen fuel tank inerting system during flight testing for both effectiveness and cost [2].

In the 1980s, ASM OBIGGS work performed by the DoD culminated in a study that highlighted the favorable life cycle costs of an on-demand inert gas generation system over a stored inerting agent system and explosive suppressant foam. This study concluded that an inerting system using state-of-the-art ASMs with HFM technology was cost-effective when compared to other technologies and allowed for a relative performance increase of a factor of ten over previous ASM technology systems [3]. The FAA evaluated the performance of a particular ASM in the 1990s in an attempt to gage the ability of these devices to generate NEA for purposes of fire suppression and inerting [4]. Recent FAA research has focused on determining the limiting oxygen concentration required to prevent a reaction in a flammable fuel tank ullage. Scale tests, using hydrocarbon-based fuel vapors, have shown that an oxygen concentration below 12 percent by volume will prevent a reaction in a flammable tank ullage with a measurable pressure rise using a variety of ignition sources [5].

<u>ASM Theory of Operation</u>. HFM are fabricated into a vessel called an ASM. When supplied with pressurized air, these modules will ventilate a waste stream of gas from a permeate port referred to as oxygen-enriched air (OEA) that is rich in oxygen, carbon dioxide, and water vapor [6]. This allows the product gas passing through the ASM to be rich in nitrogen. As flow is limited through the ASM product port (orifice), less NEA is generated, but at a lower oxygen concentration (more pure nitrogen). To provide a high-purity NEA at a low flow rate, a small orifice with a high backpressure was used. To generate less pure NEA at a high flow rate, a large orifice with a smaller backpressure was used. This operational property allows for a single OBIGGS to generate different flows and purities of NEA to optimize the system's ability to inert a fuel tank throughout a given aircraft mission. Generally, at a given altitude (permeate pressure), ASM input pressure, and ASM fiber temperature, an ASM has a fixed performance, which will drive the capabilities of a given ASM inerting system to inert a given ullage volume.

INERTING SYSTEM DESCRIPTION

<u>System Overview</u>. The FAA OBIGGS was designed to inert the center wing tank (CWT) of a 747SP (classic type). It consists of a single unregulated flow path that is plumbed to a manifold of three ASMs. The nitrogen-rich gas that passes through the modules is then plumbed to the CWT to reduce the oxygen concentration. The flow path has a heat exchanger, which controls the ASM inlet temperature, and a filter. After the ASMs, a control valve allows the system to flow in both low- and variable/high- flow modes. Figure 1 shows a block diagram, illustrating the primary components of the inerting system. The inerting system is mounted on an aluminum frame in a palletized manner to allow for simplicity of construction and installation.

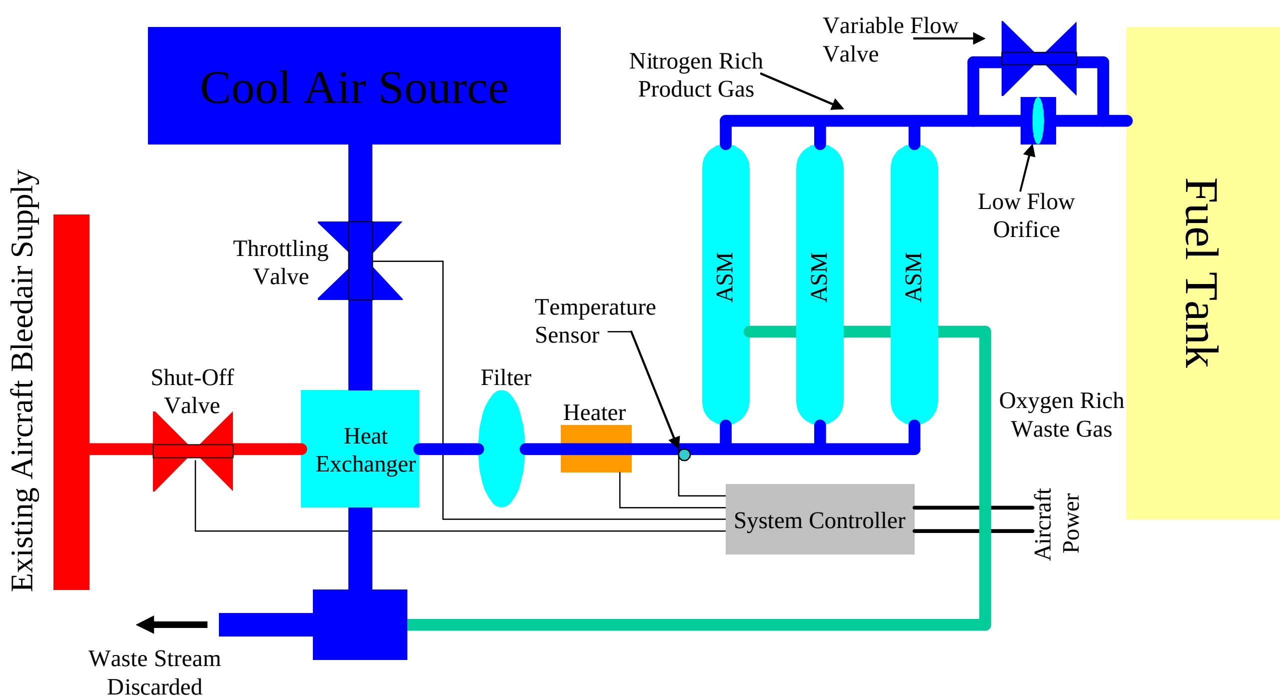

Figure 1. FAA Inerting System Block Diagram

System Flow. The inerting system operates using bleed air from an aircraft supply manifold, which is reduced down to a 2-inch-diameter tube for connection to the system shutoff valve (SOV). When energized, the SOV opens, allowing flow into the system and through the heat exchanger. The heat exchanger accepts up to 450°F bleed air and uses a cooling bypass loop to cool the system flow to an optimal operational temperature of 180°F ±10°. The cooling bypass loop uses a fan to force air through the heat exchanger and a motor-operated, modulating valve to meter the airflow. This modulating valve is operated by the system temperature controller but controlled manually with a switch box by the OBIGGS operator. The 1-inch-diameter heat exchanger bypass Y allows a portion of the system flow to bypass the heat exchanger to decrease the effectiveness of the cooling loop, giving better control of the air temperature into the ASMs.

After the heat exchanger, the bleed air then passes through a desiccating filter, a temperature sensor used by the OBIGGS operator controlling the ASM temperature, and through a section of pipe with a clamp heater before entering the ASMs via a manifold. This clamp heater is designed to increase the temperature of the ASM inlet air significantly should the temperature drop well below the target control temperature due to system heat rejection. However, it had very little effect when the ASM air temperature was close to the temperature obtained in the heat exchanger.

The 180°F bleed air is passed into the ASMs and separated into NEA and OEA constituents. The NEA portion exits the ASM outlet while the OEA portion passes out of the permeate (waste) port. The ASM waste flow is eliminated from the system through the OEA manifold, which is plumbed to an ambient pressure environment.

The NEA passes through the flow control portion of the system, which allows the system to flow at either low-flow (low-oxygen concentration) or variable/high-flow (higher oxygen concentrations) conditions. The variable/high-flow valve can be closed forcing all the flow through the low-flow orifice, or opened to one of five distinct open conditions, creating different backpressures, that provide a total of six different flow conditions. These distinct conditions could be adjusted to some extent if necessary. As the variable/high-flow valve is opened, the system backpressure will decrease, creating progressively more NEA flow, at increasing NEA oxygen concentrations (less pure nitrogen). The variable/high-flow valve was used to obtain a known backpressure with a fixed valve position, to create a single high-flow condition, to allow the OBIGGS to operate as a dual flow system when desired.

The NEA is then plumbed to the fuel tank in question in an appropriate manner

System Interfacing. To allow a relatively simple interface with the aircraft, the system pallet has six mounting points to attach brackets.

The primary mechanical interfaces for system operation were the bleed air inlet, NEA deposit, OEA discharge, and heat exchanger cooling air inlet and exit. Bleed air was supplied to the system through a sealed sleeve assembly to connect a bleed air duct to the OBIGGS SOV assembly. The system SOV is a 2-inch-diameter, solenoid-operated, mechanically closed valve with a 55 psi over-pressure protection circuit. This feature protects the system components in the event of a failure causing a bleed air overpressure.

The OBIGGS NEA deposit is mainly made of 1-inch Hydroflow™ 14J02 sleeve/coupling connection. Two check valves were employed between the system and the fuel tank to prevent fuel from seeping back to the inerting system.

The OEA discharge is a 2-inch-diameter aluminum tube with a flexible coupling for interface with the aircraft exterior. This flexible coupling was vented to ambient pressure. Failure to provide complete ambient pressure to the ASM permeate makes it difficult to predict ASM performance.

The heat exchanger cooling air inlet and exit are 4-inch-diameter flexible tubes. The inlet must be plumbed to provide fresh cooling air to the heat exchanger. This can be interfaced with the exterior of the aircraft, an air cycle machine scoop, or simply draft cabin air. The heat exchanger exit must be deposited away from the inlet to avoid recirculation of hot bypass air.

Each system part has a specified electrical connector to communicate power and signals to the individual components. The components were wired with aviation-grade wiring to a system connector, allowing the OBIGGS to easily interface to the OBIGGS control box. This box allows the system and its components to be turned on or off and to switch the system from one flow mode to the other. It also provides the system operator with the ASM inlet temperature and a manual temperature control box.

System Operation. The system is designed to operate during normal aircraft flight and ground operations, provided bleed air is available. The operator must manually turn on the OBIGGS by activating the SOV after bleed air is available on the aircraft. This usually occurs shortly after the aircraft engines are started.

The ASM input air temperature should be maintained at 180°F ±10° for efficient performance. The OBIGGS operator controls the ASM inlet temperature manually, adjusting several potentiometers that control the position of the cooling air modulating valve for the heat exchanger. This modulating valve needed to be continually adjusted due to constantly changing conditions (altitude, bleed air pressure, OBIGGS temperature) on the aircraft during a typical flight. The operator used a temperature readout display on the OBIGGS control box to monitor cooling loop performance. The readout display receives its signal from a thermocouple that was installed forward of the ASM inlet manifold. The operator could use the heat exchanger bypass valve available, if necessary, to decrease the affectivity of the heat exchanger. This could make controlling the temperature on the ASMs with the heat exchanger cooling air modulating valve easier under some conditions.

The OBIGGS did not have an automatic flow mode controller and required changing from low- to variable/high-flow mode manually. The OBIGGS was operated in either a dual-flow methodology or in a variable-flow methodology using the high/variable flow valve. With the variable/high-flow valve closed, the system operates in low-flow mode (fixed orifice). The operator could then open the variable/high valve in increments to obtain increasingly higher flows with corresponding lower NEA purities to vary the system output as conditions require. This valve was also used with a known backpressure with given input conditions to use the OBIGGS in a dual-flow methodology. Variable/high-flow mode allows greater flow into the tank during aircraft descent to minimize air entry into the ullage due to increasing static air pressure. This produced a resulting ullage oxygen concentration less than if the low-flow mode was simply employed the entire flight cycle. The variable flow was used to increase NEA flow at the top of descent over and above the capabilities of a single high-flow mode to reduced the amount of air entering the fuel tank ullage. It was also used to flow less of a lower oxygen concentration NEA (more pure nitrogen) into the tank during low-level altitude holds to potentially improve the overall average tank oxygen concentration at landing.

The system low-flow conditions were established by setting a needle valve during ground operation. Low-flow mode was set to generate 5 percent oxygen NEA at sea level, given some predetermined bleed air pressure. When necessary, the high-flow orifice was set to generate 11 percent NEA at sea level. Needle valves were used to adjust the backpressure needed during ground operations to allow the system to provide the desired variable performance throughout the flight profile. When the variable/high-flow valve was used to allow for varying the oxygen concentration and flow of the OBIGGS during flight, the opening and closing of the valve provided the changing system backpressure. The low-flow mode was primarily used for ground taxi, takeoff, climb, and cruise phases of flight, while the variable/high-flow mode was used mainly for the descent phase of flight.

SYSTEM EVALUATION TEST ARTICLES

747SP Ground Test Article. A decommissioned Boeing 747SP was used to perform full-scale fuel tank inerting ground tests on a commercial transport airplane. It has a maximum gross takeoff weight of 696,000 lbs with an empty dry weight of approximately 330,000 lbs. The aircraft has four underwing engines and an auxiliary power unit in the tail area. It has a wing span of 196 feet, and an overall aircraft length of 185 feet.

The test article is supplied with independent ground power for instrumentation, heating and air conditioning, and equipment and accessories for complete operation of the instrumentation independent of the operation of the aircraft. The cabin was fitted with a climate-controlled instrumentation room where all instrumentation and associated equipment was routed, housed, and wired to an extensive data acquisition system.

Figure 2. OBIGGS Installed in Boeing 747 SP Ground Test Article Pack Bay

Immediately below the CWT are three air cycle machines that provide conditioned air to the aircraft and reject heat in what is called the pack bay area. Figure 2 illustrates the FAA OBIGGS installed in the area known as the empty pack bay, which is the aft, right-hand side of the pack bay area. The OBIGGS had six thermocouples and four pressure taps plumbed to a bank of pressure transducers, installed to monitor OBIGGS health and performance. It also had gas sample ports plumbed to oxygen analyzers in the instrumentation room to measure both NEA and OEA oxygen concentrations. Additionally, a mass flow meter was installed at the NEA output to measure the NEA flow rate. An extensive array of thermocouples monitored temperature throughout the pack bay area. Reference 7 gives a more detailed description of the 747SP ground test article instrumented for the study of ground-based inerting.

Airbus A320. To validate the dynamic performance of an ASM through a typical commercial transport flight cycle and validate the dual flow methodology, Airbus provided an A320 with associated instrumentation and data acquisition system. The aircraft has a basic operating weight of 93,079 lb with a gross takeoff weight of 162,040 lb. It has a 112-foot wing span and is 123 feet long. The maximum cruise speed of the aircraft is 487 knots at an altitude of 28,000 feet with a ceiling of 43,000 feet.

The FAA OBIGGS with associated instrumentation was installed in the cargo bay (figure 3) and was equipped with instrumentation to monitor and set OBIGGS parameters. The OBIGGS had six thermocouples and four pressure transducers installed to monitor OBIGGS health and performance. The OBIGGS was also equipped with gas sample ports to measure both NEA and OEA oxygen concentrations. Additionally, a totalizing mass flow meter was installed at the NEA output to measure the NEA flow rate [8].

Figure 3. System Installed in A320 Cargo Bay

NASA 747 SCA. To evaluate the complete inerting system installed as designed, the NASA 747 Shuttle Carrier Aircraft (SCA) was employed, which is a highly modified Boeing 747 used to transport the Space Shuttle Orbiter. It has a basic operating weight of 318,053 pounds with a gross taxi weight of 713,000 pounds. It has a 195' 8" wing span and is 231' 10" long. The maximum cruise speed of the aircraft is 250 knots or Mach 0.6 at an altitude of 26,000 feet with a maximum ceiling limited by the Mach limitation and stall speed.

The NASA 747 SCA testing employed essentially the same OBIGGS instrumentation as the 747SP ground test article, as well as having several temperature measurements in the pack bay area and a static pressure sensor. Figure 4 shows a three-dimensional rendering of the OBIGGS installation in a Boeing 747 pack bay with the existing 8-inch-diameter bleed air duct in blue as a spatial reference. Reference 9 gives a more detailed description of the instrumentation employed on the NASA 747 SCA.

CALCULATIONS

OBIGGS bleed air flow was calculated from equations for flow in and out of the ASM and a mole balance of oxygen for the ASM. Combining theses two equations gives the following equation for bleed air flow in terms of NEA flow. Reference 8 gives a more complete derivation of the equation.

$$\dot{Q}_{Bleed} = \dot{Q}_{NEA} \cdot \frac{([O_2]_{NEA} - [O_2]_{Perm})}{(0.21 - [O_2]_{Perm})} \qquad (1)$$

With: $[O_2]_{NEA}$ = NEA Oxygen Concentration

$[O_2]_{Perm}$ = OEA Oxygen Concentration

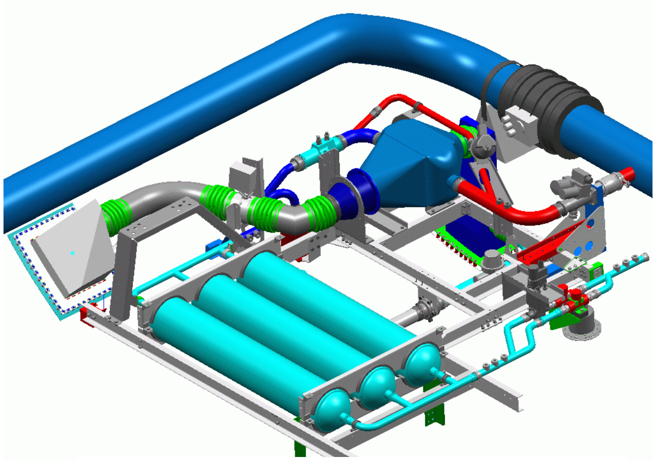

Figure 4. Three-Dimensional Rendering of System in 747 Pack Bay

PERFORMANCE RESULTS

Initial Ground Test. The FAA OBIGGS provided a somewhat wide range of performance, given similar input parameters and operating conditions. Figure 5 shows that the OBIGGS provided 10 to 20 percent greater performance on the 747SP ground test article at sea level than predicted by the manufacturer's data. This was not unexpected because the manufacturer's data was based on a single ASM static test. Each ASM will perform slightly different due to subtle dissimilarities in manufacture and assembly. The difference in performance on different days during validation measurements was attributed to different ambient temperatures and OBIGGS environment temperatures. Although a somewhat constant ASM input temperature and pressure was maintained over an extended period of time, it appears an isothermal environment is needed to get completely stable performance data.

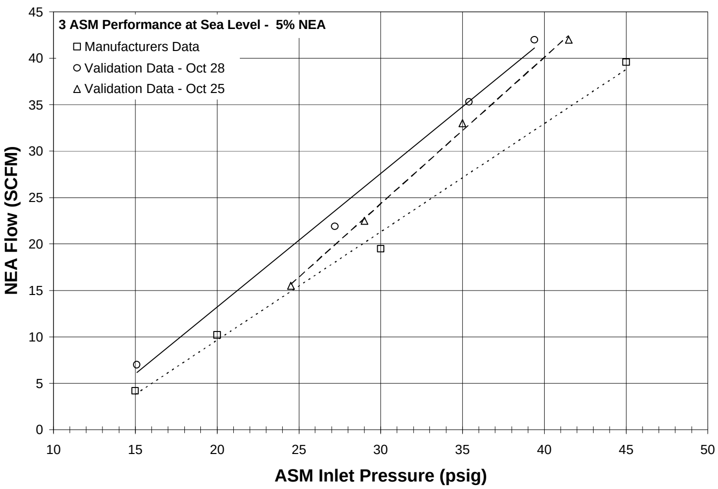

Figure 5. ASM Performance Validation Data

Single ASM Flight Test Data. The difficulty in obtaining stable ASM performance data is evident when examining data acquired by using the OBIGGS with only one ASM in the dual-flow methodology on the Airbus A320, compared to static test data obtained from the manufacturer (figure 6). Although some of the data compares well, most deviate in some manner from what was expected. This highlights the difficulty in obtaining stable conditions on an aircraft to validate static test stand data. The only evident stable conditions (bleed air pressure, ASM temperature, and altitude) occur during cruise, which does not guarantee the temperature stability of the environment of the OBIGGS, which allows for a stable ASM temperature. It should also be noted that the OBIGGS could not obtain the target temperature of 180° F during a variety of test conditions on the A320 test aircraft. Regardless of specific operational short comings, it is critical to evaluate an OBIGGS throughout an entire flight cycle, and determine the effect of the OBIGGS performance on the fuel tank in question, to determine the effectiveness of the inerting system for a specific application.

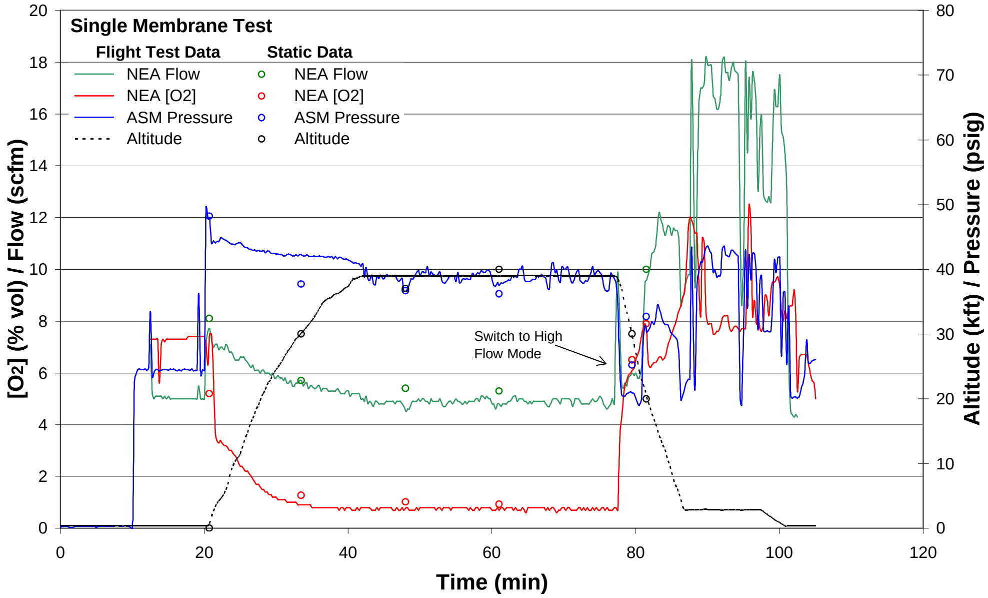

Figure 6. Dynamic ASM Performance Data From the A320 Flight Test Article

The flight test data in figure 6 illustrates the expected relationship between ASM pressure and NEA flow. An increase in pressure on the ASM resulted in greater NEA flow and a lower NEA oxygen concentration (more pure nitrogen). In general, increasing ASM inlet pressure will increase NEA flow and purity (decreasing oxygen concentration) simultaneously, given a fixed outflow orifice setting. This is due to the fact that an increase in flow across a fixed orifice will result in a greater pressure drop, and an increase in pressure drop across the system flow orifice will result in a decrease in oxygen concentration. Decreasing atmospheric pressure during ascent will increase the separating efficiency of the membrane module, having the effect of decreasing the flow and increasing the purity. During the descent, a high-flow mode is selected, giving an instantaneous increase in flow and decrease in purity.

The effect of the dynamic OBIGGS performance on the bleed air consumed was calculated using equation 1. Figure 7 illustrates the profound influence permeate pressure (altitude) has on the bleed air consumed by the OBIGGS. The graph illustrates the effect of increased selectivity and permeability of the ASM with altitude. It can be implied by examining equation 1 with figure 6 that as NEA oxygen concentration decreases, OEA oxygen concentration decreases. This nonintuitive relationship is the result of the permeability characteristics of the HFMs in the ASM, that generates more pure NEA by essentially venting greater quantities of air, which is mostly nitrogen [7]. In the beginning of the test, at sea level, the ASM generated 5 standard cubic feet per minute (SCFM) of NEA at 5 percent oxygen concentration and was consuming 14 SCFM of bleed air. At cruise, the OBIGGS is generating 4 SCFM of less then 1 percent NEA but was consuming almost 50 SCFM of bleed air. The increased permeability and selectivity of the ASM at altitude allowed excellent production of NEA at altitude, especially when considering the effect of 4 SCFM on

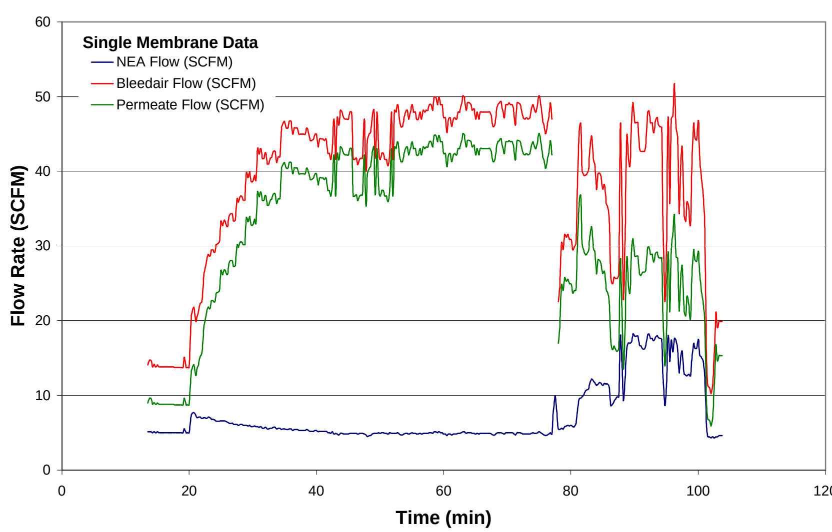

Figure 7. Calculated Bleed Air Consumption Data From the A320 Flight Test Article

inerting the tank is 5 fold greater than at sea level. Also, 1 percent NEA is a much more efficient inerting agent the 5 percent NEA. However, the OBIGGS discarded more than three times the amount of bleed air to obtain that efficiency.

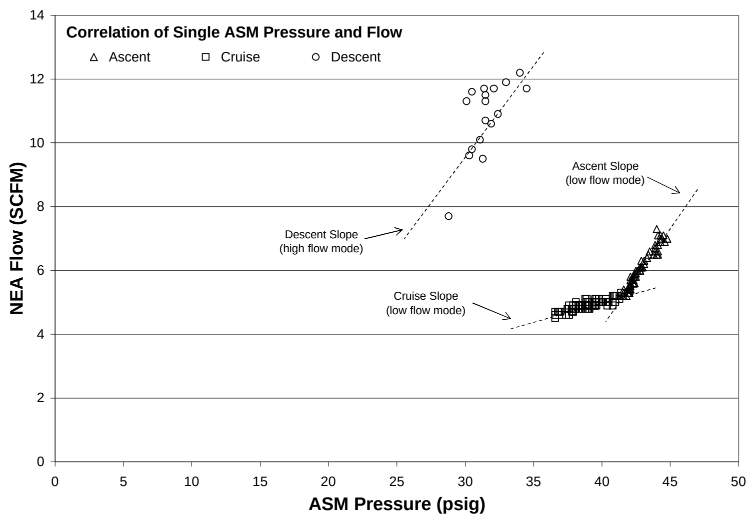

Figure 8. ASM Pressure/Flow Correlation

The relationship between ASM pressure and NEA flow is correlated in figure 8 for a small portion of a typical A320 flight test. This correlation is only valid for a similar flight profile with bleed air schedule, as NEA flow is a strong function of pressure altitude. This is why the cruise slope is much less then the ascent and descent slopes. The changing altitude causes vast changes in membrane permeability and a wider range in NEA flows, while the cruise portion of the flight exhibits no altitude change effects and, thus, gives a true correlation between pressure and flow with the given low-flow fixed orifice at 39,000 feet. Reference 7 discusses correlation of performance data in depth.

Complete Inerting System Performance Data. The stable performance of the OBIGGS using all three ASMs was examined on the NASA 747 SCA flight test article (figure 9) for several flight altitudes. This data shows the expected relationship between flow and purity as well as the variation of performance with altitude. This data was acquired with as consistent ASM pressure as possible on the flight test article. Other data points were acquired with this data set, but exhibited inconsistent trends with this data. This was probably due to the fact that the OBIGGS was not completely warmed up, given the fact that the data points in question were all acquired immediately after takeoff.

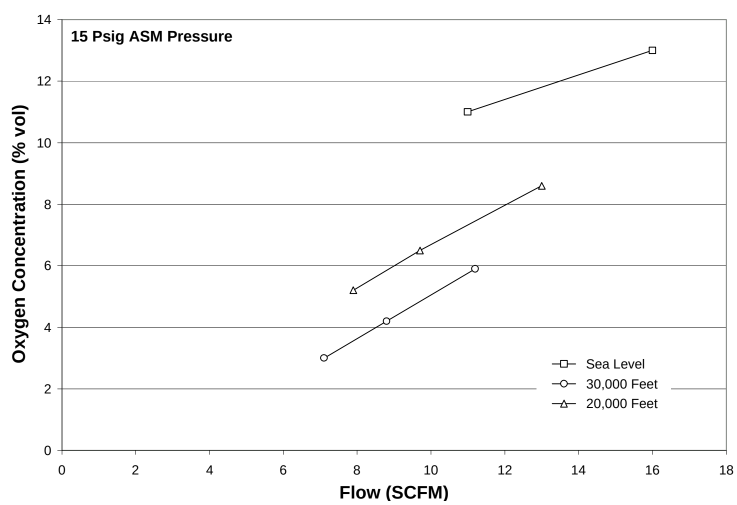

Figure 9. FAA OBIGGS Static Performance Data

When examining the dynamic performance of the FAA inerting system, it became apparent after the first test that the cruise portion of the flight provided essentially stable OBIGGS performance. The primary focus of the dynamic performance analysis was the taxi/takeoff portion of the flight and the descent/landing portion of the flight. The primary factors effecting performance were the ASM supply pressure, the permeate pressure (static altitude pressure), and the ASM temperature. Tests with these characteristics in common were compared for consistency. The OBIGGS performance, in terms of NEA purity and flow for these three tests with similar pressure profiles, is compared in figures 10 and 11, respectively, for the taxi/takeoff portion of the flight cycle. Each test had an adjusted time to allow for comparison of the parameters. These tests should exhibit very similar characteristics, particularly from the time of takeoff through the first 4 minutes of flight [8]. However, the system NEA flow was somewhat varied for this time period. This variation in performance is linked to the difference in system warmup before each test. Although each test used the same ASM input temperature (180°F ± 10°), the NEA temperatures were very different for this portion of the flight, indicating the OBIGGS had not been fully warmed up and the ASMs were not heat soaked (stable temperature), given the OBIGGS environment temperature.

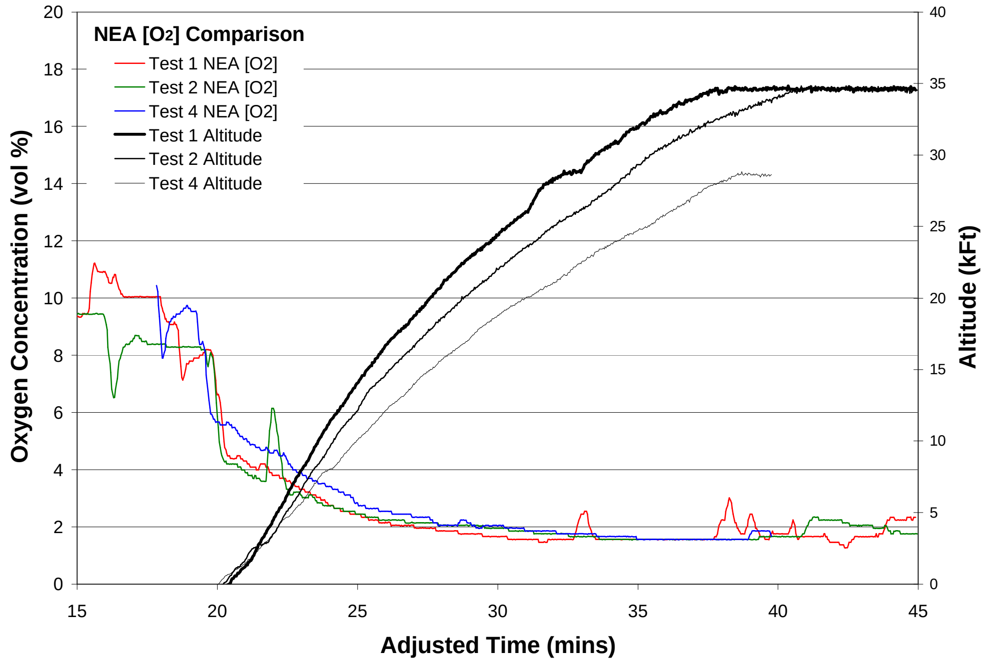

Figure 10. FAA OBIGGS NEA O_2 Concentration Data During Ascent on the NASA 747 SCA

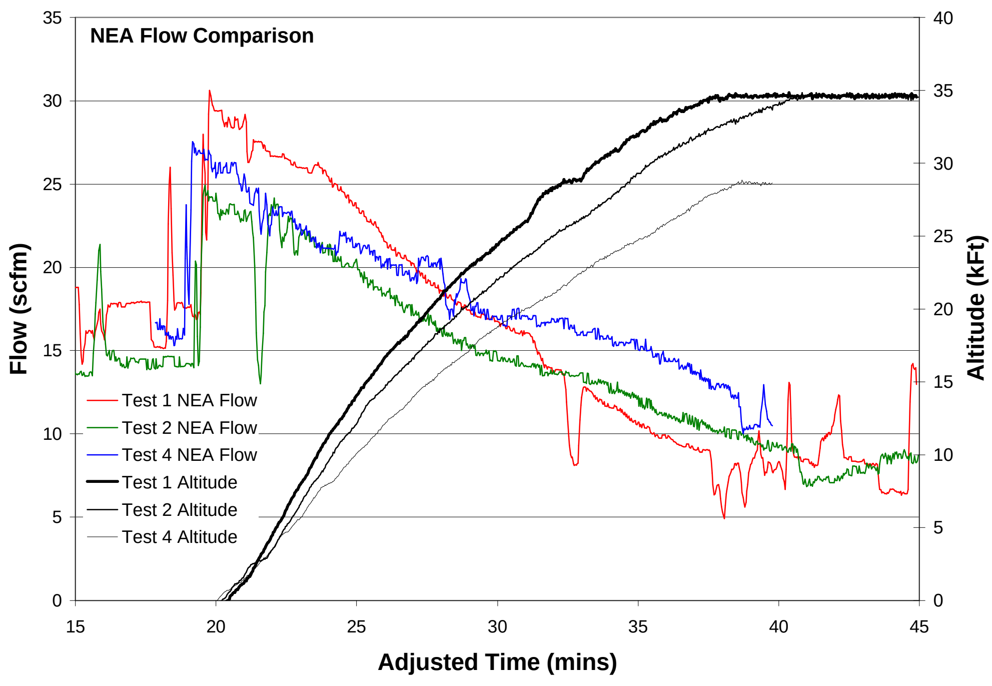

Figure 11. FAA OBIGGS NEA Flow Data During Ascent on the NASA 747 SCA

The OBIGGS performance, in terms of NEA purity and flow for three tests with similar pressure profiles, is compared in figures 12 and 13, respectively, for the descent/landing portion of the flight cycle. Test 1 was performed using the traditional dual-flow methodology, while tests 2 and 3 used a variable-flow methodology during descent with test three having the largest effective orifice (least back pressure), and test 2 had a somewhat smaller effective orifice [8]. As expected, figures 12 and 13 illustrate that tests 2 and 3 with potentially larger high-flow orifices delivered a resulting higher volumes of NEA with a resulting higher oxygen concentration (less pure nitrogen), particularly at the bottom of descent. High NEA flow during descent is designed to reduce the flow of air into the CWT through the vent system, and thus, a net lower oxygen concentration in the tank after the completion of descent. Note the erratic nature of the ASM flow and purity at the end of descent makes it difficult to judge what tests had a greater flow into the CWT. This is due to the very dynamic nature of the engine throttle settings during the final stages of flight that create large erratic ASM pressure changes during that time.

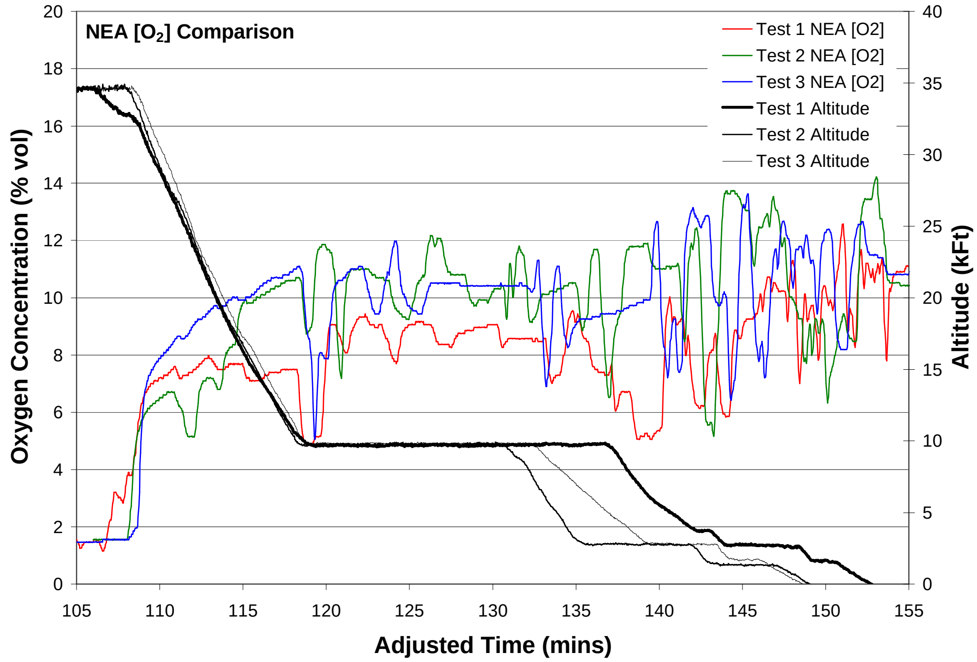

Figure 12. FAA OBIGGS NEA O_2 Concentration Data During Descent on the NASA 747 SCA

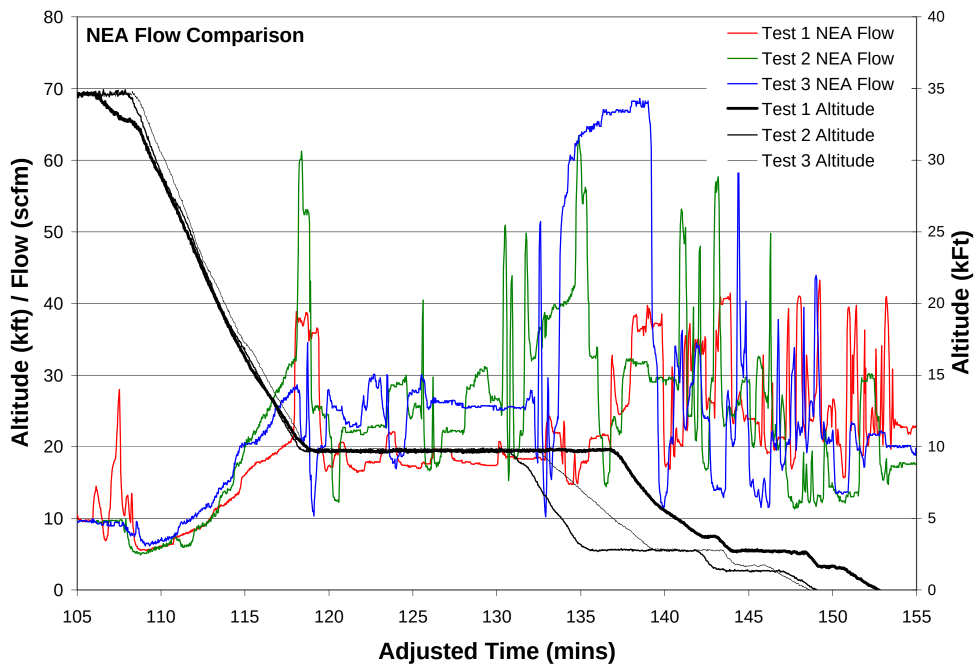

Figure 13. FAA OBIGGS NEA Flow Data During Descent on the NASA 747 SCA

It should be noted that these three tests exhibit the identical bleed air consumption even though tests 2 and 3 have considerably greater NEA flow. Since the descent profiles provide virtually the same input parameters to the OBIGGS, the performance of the ASM will be similar. Any performance differences due to heat soaking the OBIGGS have been realized since the system has been at altitude for some time with similar input conditions across all three tests. Tests 2 and 3 simply varied the output conditions to achieve a greater OBIGGS flow, which allows less air to enter the fuel tank through the vent system during descent. This apparently had very little effect on bleed air consumption.

SUMMARY

Through research, testing, and analysis, the Fire Safety Branch of the FAA developed a prototype fuel tank inerting system designed to inert the CWT of a classic Boeing 747 during normal flight and ground operations. The results of initial ground testing indicated it could be difficult to duplicate OBIGGS performance numbers acquired during static testing, probably due to the difficulty in obtaining stable temperature conditions within the ASMs on an aircraft test bed. The results of OBIGGS testing on aircraft indicated that the system concept was valid and that the air separation module dynamic characteristics were as expected given the limited scope of testing discussed here. Both single ASM and complete system (three ASM) configuration tests gave the expected performance with ASM pressure having the expected effect on flow rate. Bleed air consumption was greater than expected for some tests. Additional research is needed to determine what changes in system design or operational methodology would best reduce the bleed air flow and the associated cost. Any deviations in OBIGGS performance from test to test could be explained by the difference in warmup times proceeding system operation that day. The use of the variable flow mode did allow for a greater amount of NEA to be generated on descent at a higher oxygen concentration with flow being as much as 50% greater for short periods of time then when simply employing a single high-flow mode.

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