

DEMONSTRATION TESTING FOR GROUND SERVICING OF THE COMMERCIAL CREW VEHICLE EMERGENCY BREATHING AIR ASSEMBLY

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ABSTRACT

The new Commercial crew vehicle (CCV) Emergency Breathing Air Assembly (CEBAA) is a Composite Overwrapped Pressure Vessel (COPV) filled with high-pressure air, which is designed to provide portable emergency breathing air for up to five crew in the event of an ammonia leak aboard the International Space Station (ISS). Industrially, several common methods of delivering breathing air exist; however, ground processing constraints and flight requirements necessitate the more unusual approach of servicing a COPV with high purity gaseous nitrogen and oxygen serially to achieve a specific mixture of breathing air at approximately 4000 PSIA. A dwell period allows the gases to mix before sampling for composition verification. The novelty of this approach led to concerns about acceptable gas mixing and the ability to deliver accurate gas compositions. Tests examining mixing rate over a series of post-servicing dwell periods were conducted to determine the optimal time for achieving a homogeneous mixture. Further testing was conducted to examine process accuracy using temperature-pressure load criteria to target a specific concentration of oxygen and nitrogen. Test results show that while some stratification of nitrogen and oxygen was observed, a seven-day dwell is adequate time to achieve an acceptable level of mixing, and that existing ground support equipment can accurately service CEBAA COPVs to the required temperature, pressure and composition for flight.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

CCV	Commercial Crew Vehicle
CEBAA	CCV Emergency Breathing Air Assembly
COPV	Composite Overwrapped Pressure Vessel
GSE	Ground Support Equipment
ISS	International Space Station
Mol%	Mole Percent

N2	Nitrogen
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
O2	Oxygen
PSIA	Pounds per Square Inch Absolute
REFPROP	Reference fluid Properties
ρ_{n,N_2}	Molar density of nitrogen
$\rho_{n,mix}$	Molar density of nitrogen-oxygen mixture
x_{n,O_2}	Mole fraction oxygen
$\rho_{n,mix,adj}$	Molar density of the mixture adjusted for nitrogen fill error

INTRODUCTION

The International Space Station (ISS) houses an international team of astronauts to facilitate academic, commercial, and government research and maintain an orbiting laboratory for the continued exploration of space. High purity anhydrous ammonia is used as a refrigerant in ISS thermal control systems and due to its toxic properties, particularly when inhaled, anhydrous ammonia poses a significant threat to the safety of astronauts. Therefore, precautions are taken to prevent crew contact with ammonia, so contingency plans are in place to ensure safety of the crew if ammonia leaks into the ISS cabin. With Commercial crew vehicles (CCV) soon transporting crew to and from the ISS, NASA has developed the CCV Emergency Breathing Air Assembly (CEBAA) to support contingency evacuation operations in the event of an ammonia leak.

The CEBAA will provide temporary portable emergency breathing air to the ISS crew while they evacuate to a CCV. Once the crew reaches the capsule, they continue using CEBAA to breathe until the CCV scrubbers reduce ammonia vapors within the CCV cabin to acceptable levels before undocking. The CEBAA consists of a COPV, pressure regulator, and hoses that connect to existing ISS portable breathing air masks. The COPV must be filled with breathing air prior to launch to ISS.

PROBLEM BACKGROUND

The primary CEBA flight servicing requirements pertain to air quality inside the tank and quantity of air contained within the tank. These specifications are based on the needs of five astronauts breathing from one COPV for up to one hour as well as flammability limits of materials within the cabin.

The CEBA will interface with existing emergency breathing air equipment on the ISS, and therefore the assembly uses some heritage flight hardware from other systems. The CEBA COPV is the same tank used to transport oxygen and nitrogen to the ISS via the Nitrogen/Oxygen Recharge System (NORS). Dedicated ground support equipment (GSE) at the Kennedy Space Center pressurizes NORS COPVs (Reference Figure 1) with pure nitrogen or oxygen. This GSE delivers the commodities separately, yet uses a common flow path to interface with the COPV. Since the COPV interface is the same for NORS and CEBA, it is advantageous to utilize this demonstrated capability if use of the unmodified NORS GSE is practical. Therefore, the problem reduces to developing a process that accurately delivers the correct quantity and concentration of air using the existing NORS GSE.



Figure 1. Nitrogen/Oxygen Recharge System Tank

PROPOSED SOLUTION

The proposed solution serially pressurizes a CEBA COPV with nitrogen then oxygen. Once both gases are added, they are left to mix for seven days to abate any stratification that may occur during the serialized filling operations. Finally, samples are taken to verify proper concentration.

Process

The process begins by establishing the density and concentration of the target load, then computing the pressurization profile based on this objective. Because the NORS GSE uses pressure and temperature indication for tank loading, the profile is translated into a temperature and pressure target for the first gas. The choice of the first gas is arbitrary with regard to the process, but it is operationally beneficial to add nitrogen first. Nitrogen is required for particulate and hydrocarbon sampling before oxygen can be introduced into the system, therefore loading nitrogen first streamlines the process.

Since nitrogen and oxygen are added serially, capability for accurately computing target fill pressures for each gas addition is critical. Typically, this would be completed using Dalton's law, which arises from a material balance combined with the ideal gas law; however non-idealities at CEBA operating pressures incur too much error to reliably meet concentration requirements. Consequently, a different approach is necessary. By returning to the basic material balance used by Dalton's law and replacing the ideal gas law with a more accurate equation of state, errors are reduced to an acceptable level. Since the fill process fundamentally includes a mixing problem, and Helmholtz equations of state are advantageous for their convenient application to mixing problems, a Helmholtz model was selected for the process calculations. The National Institute of Standards and Technology (NIST) Reference Fluid thermodynamic and transport Properties database (REFPROP) software package provides these models, so process calculations use REFPROP for equation of state data.

Using the target air density and concentration, the mass of nitrogen in the target load can be computed in Equation 1.

$$\rho_{n,N_2} = (1 - x_{n,O_2}) \cdot \rho_{n,mix} \quad \text{Equation 1}$$

The density is converted into temperature and pressure guidelines using data from REFPROP, which is used to pressurize the COPV with the specified level of nitrogen.

Once the nitrogen fill is complete, the COPV is allowed to reach thermal equilibrium. An optional top-off following thermal stabilization allows adjustment if the nitrogen charge is significantly off-target, but the process tolerates errors in the initial nitrogen fill by tuning the addition of oxygen to match. Thermal stabilization after pressurizing the COPV with nitrogen is critical because an accurate temperature and pressure is necessary for computing the subsequent oxygen charge.

Using the stabilized temperature and pressure of the nitrogen fill, the density of nitrogen in the tank, $\rho_{n,N_2}(T_{fill}, P_{fill})$, is computed.

The density of nitrogen in the tank is then used with the target concentration of oxygen to compute the target temperature and pressure of the oxygen addition in Equation 2.

$$\rho_{n,mix,adj} = \frac{\rho_{n,N_2}}{(1 - x_{n,O_2})} \quad \text{Equation 1}$$

After oxygen is added to the COPV and a reasonable thermal equilibrium is achieved, an optional top-off provides means for fine adjustment of the oxygen addition. The oxygen addition must be very accurate to meet flight concentration requirements. It is important to note that gas adjustments can only be made through additional pressurization because venting could skew the concentration by disproportionately venting oxygen or nitrogen. Once the oxygen fill criteria are met, the COPV is isolated for seven days so the nitrogen and oxygen can mix. Samples are then taken to verify concentration requirements are met before final flight preparations are made.

Concerns

Due to the unusual nature of the problem, several concerns about the fitness of the process arose during its development.

Mixing Effects

The oxygen addition end pressure calculation uses a mixture at the target concentration to compute the end temperature and pressures for the fill. This incorporates all mixing departure functions into the temperature pressure relationship as if the nitrogen and oxygen are completely mixed in the tank, but the nitrogen and oxygen are certainly not fully mixed at this point. This is a source of error, but it is unlikely to be very large because nitrogen and oxygen are similar gases and they form a nearly ideal mixture. This scenario is bounded by the completely separate ideal mixture model and completely mixed REFPROP model cases which are very similar indicating nearly ideal mixture behavior. Since the two models have very similar predictions, this is not expected to be a significant source of error in the fill process.

Accuracy

The tolerance on the concentration is very narrow at 0.5% mol. This raises concerns about margin for human or instrumentation error especially since the target range must be derated to account for error in sampling methods. Bounding estimates indicate that pressurization can adequately be controlled using current operational procedures given that the system is near thermal equilibrium at process critical pressures.

Mixing Rate

Diffusion rates of gases are greatly reduced under high pressure due to decreased free space within the container. Since nitrogen and oxygen are added serially in the proposed CEBA servicing process, there is concern that the diffusion rate may be insufficient to achieve complete mixing within a reasonable span of time. A conservative bounding estimate diffusion model suggests roughly 30 days for mixing to settle within tolerance throughout the tank, but

actual settling time is expected to be much lower due to turbulence in the tank generated during the filling process.

TESTING

Given the challenges of servicing the COPV serially, testing was divided into two-phases to address the concerns of stratification and process accuracy separately.

Stratification

Stratification testing consisted of servicing a test tank with a specific ratio of nitrogen and oxygen then allowing the tank to mix over a controlled test period. At the conclusion of the dwell, a series of purity samples were collected at various pressures to determine whether the tank contents were adequately mixed. Weight measurements recorded before and after the addition of both nitrogen and oxygen were used to corroborate sample results. Because the servicing process is time consuming, the initial dwell duration choice was based on a combination of coarse diffusion estimates and processing schedule. The dwell was minimized so that servicing could be completed in a reasonable time to support launch schedules. The first iteration of stratification testing dwelled over a period of two days and was increased as necessary based on concentration sample results.

Accuracy

Tests for accuracy were almost identical to the stratification tests with emphasis on concentration and pressure specifications and less focus on mixing investigation. Fewer samples were necessary for these tests since homogeneity is not in question after the previous testing phase. Three attempts were made using the proposed process, and the oxygen concentration analyzed to determine if the process met accuracy requirements. Furthermore, one additional attempt intentionally missed the target oxygen content then added more oxygen to correct the intentional error.

RESULTS

Stratification Testing

Four iterations of stratification testing were performed with three purity samples between 1500 and 4000 PSIA taken during each trial. A summary of the data is tabulated in Table 1 below.

Table 1. Stratification Test Results

Trial	Sample 1 O ₂ Concentration Deviation from Target (mol%)	Sample 2 O ₂ Concentration Deviation from Target (mol%)	Sample 3 O ₂ Concentration Deviation from Target (mol%)	Dwell Time (Days)
1	0.78	-0.12	-0.12	2
2	0.03	0.07	0.03	7
3	0.06	0.06	0.16	7
4	0.08	0.08	-0.02	7

The first trial exhibited signs of minor stratification after two days of mixing. A new dwell time of seven days was chosen loosely based on the deviation size and processing time considerations. The subsequent three trials showed no significant signs of separation after seven days of mixing.

Because there was no clearly recognizable trend in oxygen concentration and samples from trials 2-4 were all within 0.1 mol% oxygen of the other samples within the same trial, it was concluded that a dwell time of seven days is adequate to achieve acceptable mixing without stratification.

Accuracy Testing

Data from the seven-day dwell trials shows no discernable stratification. Furthermore, all concentration data points were on-target and within tolerance. Since the planned test methods for stratification and accuracy are nearly identical, the results from stratification trials support conclusions about process accuracy. Therefore, no further accuracy testing was performed.

CONCLUSIONS

Test results show that the described process calculations and methods used to fill a COPV serially with nitrogen and oxygen achieve an air mixture within 0.5mol% oxygen at flight pressures of approximately 4000 PSIA. Once the COPV is serviced and has reached thermal equilibrium, a dwell time of seven days produces a nearly homogenous gas such that stratification phenomena are not detected. As a result, the NORS GSE will be used to service CEBA COPVs to the required temperature, pressure and composition for emergency breathing systems on the ISS.