Reassessing the Purge Valve Architecture in the Exploration Extravehicular Mobility Unit

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Earlier designs of the xEMU purge valve architecture mimicked the design of the ISS/Shuttle EMU architecture with the use of two purge valves. When opened, both purge valves will allow suit gas to flow from the pressurized suit volume to the ambient environment. One valve provides a short duration, high flow rate emergency purge, as well as a pre-EVA nitrogen purge, while the other provides a long duration, low flow rate emergency purge.

The nitrogen present in the suit must be purged to increase the suit oxygen concentration to greater than 95% prior to initiating the pre-breathe protocol. Removing most of the nitrogen in the suit minimizes the onset of decompression sickness, while maintaining the critical partial pressure of oxygen in the suit necessary to support life at the EVA suit pressure of 4.3 psia. It is preferential for the nitrogen purging process to occur efficiently to minimize the duration of pre-EVA operations.

The purge valves additionally provide emergency oxygen flow in the event of a failure. Either purge valve is used during emergency EVA operations when the ventilation loop is not providing conditioned oxygen or sufficiently removing carbon dioxide from the helmet. In the event of this scenario, the purge valve is activated, thus causing reduction in the suit pressure. The regulators respond by flowing oxygen to maintain the pressure set point.

One potential goal of this assessment is to evaluate the possibility of eliminating the high flow purge valve if the low flow purge valve can adequately provide nitrogen and emergency purge functions. The architecture will be significantly simplified with a single purge valve. This paper will detail the purge routing design concepts considered and the methods used to analyze the suitability of potential designs, to ensure that the CO2 washout and nitrogen purge requirements are met.

Nomenclature

$A_{orifice}$ = Open Area of an Orifice
CO_2 = Gaseous Carbon Dioxide
CFD = Computational Fluid Dynamics
C_p = Specific Heat at Constant Pressure
C_{long} = Flow Coefficient for a Long Orifice
C_v = Specific Heat at Constant Volume
DCU = Display and Control Unit
EVA = Extra Vehicular Activity

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FWSA	=	Feed Water Supply Assembly
HFPV	=	High Flow Purge Valve
HUT	=	Hard Upper Torso
γ	=	Specific Heat Ratio
LFPV	=	Low Flow Purge Valve
M	=	Molar mass
$\dot{m}$	=	Mass Flow Rate Through an Orifice
M_O	=	Mach Number of Flow Through an Orifice
MSPV	=	Multi-position Suit Purge Valve
O_2	=	Gaseous Oxygen
P_{cabin}	=	Cabin Pressure
P_{suit}	=	Suit Pressure
PGS	=	Pressure Garment Subsystem
PLSS	=	Personal Life Support System
pp	=	Partial Pressure
r	=	Pressure Ratio
R_{gas}	=	Gas Constant
R	=	Universal Gas Constant
TCC	=	Trace Contaminate Control
UDF	=	User Defined Function
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

THE purpose of including purge valves into the design of the Exploration Extravehicular Mobility Unit (xEMU) is to open the suit to the ambient environment, inducing flow out of the suit by the pressure differential. Removal of gas from the Pressure Garment Subsystem (PGS) dually functions during nominal operations by removing nitrogen (N_2) from the suit prior to an Extravehicular Activity (EVA), as well as aids in emergency scenarios by removing metabolic waste and inducing flow from the oxygen (O_2) tanks while performing an EVA.

Subsequent to a crewmember's donning during nominal pre-EVA operations, the nitrogen present in the suit must be removed before the crewmember can proceed with the pre-breathe. The process of removing the nitrogen from the suit, referred to at the nitrogen purge, is achieved by first pressurizing the suit above cabin pressure, then opening either the high flow, or low flow purge valve to allow gas to vent from the suit. When the suit reaches a predefined pressure setpoint, the regulator will turn on, and maintain the suit pressure by supplying pure oxygen. The purging process is completed when the gas in the suit is comprised of 95% oxygen.

Purging nitrogen from the suit prior to performing the pre-breathe is essential in ensuring the safety and comfort of the crewmember. If the oxygen concentration in the suit in lower than 95%, the crewmember is at risk for experiencing Nitrogen Decompression Sickness (the bends) during EVA. Maintaining a 95% oxygen concentration in the suit additionally ensures that the suit environment provides the necessary partial pressure of oxygen at EVA pressure, which is less than standard atmospheric.

The hatch, which is located in between the PGS and Personal Life Support System (PLSS), houses the Feed Water Supply Assembly (FWSA). To prevent the intrusion of water from the hatch into the PGS in the event of a FWSA failure or leakage, a Zitex G-115 membrane covers the open interface between the hatch and the PGS. The pore diameter of the Zitex membrane is large enough to allow for the exchange of gas molecules between the two volumes, but not the exchange of water molecules. Because gas exchange between the hatch and PGS is to be considered, the nitrogen concentration in the hatch, along with the gaseous flow capabilities across the Zitex membrane must be considered when determining the length of time required to purge the suit of nitrogen. A relatively quick nitrogen purge is considered beneficial and contributes to a more efficient pre-EVA operations process.

The same system is used in emergency scenarios while performing an EVA when any flow failure occurs that disrupts the supply of oxygen to the crewmember such as Rapid Cycle Amine (RCA) switch bed failure or oxygen regulator failure. When the valve is opened gas flows out of the suit, causing a decrease in suit pressure. Additional oxygen is subsequently supplied by the primary and secondary tanks such that the suit is held at the pressure setpoint and the crewmember continues to receive oxygen.

In opening the suit to vacuum, the purge valve not only induces the flow of oxygen through the regulator, but also removes metabolic waste from the suit. The efficiency with which this process occurs is paramount to the crew member's safety as the accumulation of carbon dioxide (CO_2) around the mouth can result in Hypoxia (oxygen deprivation), and in extreme cases fatality. The ability of the purge valve to remove metabolic waste from the suit is quantified by performing a CO_2 washout analysis using Computational Fluid Dynamics (CFD) software during which the crewmembers resulting inhaled partial pressure of CO_2 must remain less than 20 mm Hg to ensure the comfort and safety of the crewmember.

In previous iterations of the xEMU design, two purge valves where incorporated into the suit's architecture; a valve capable of high flow, short duration purge, and a separate valve capable of low flow, comparatively long duration purge sequences. The low flow valve, capable of removing 1.55 – 1.69 pph under emergency purge conditions, removed gas from the helmet of the suit and was located over the shoulder of the Hard Upper Torso (HUT). The high flow valve, capable of removing 3.15-3.38 pph under emergency purge conditions, connected to the vent tree and was located on the Display and Control Unit (DCU) on the front of the suit HUT. While the high flow valve enables a quicker nitrogen purge prior to EVA, use of the low flow valve during an emergency scenario on EVA doubles the time to return to the air lock from 30 minutes (using the high flow valve) to an hour, which the current requirement for emergency return time. Concerns over the use of the low flow valve revolve around its nonideal location over the right shoulder of the HUT; the valve can only be accessed by one hand and is a blind operation that relies on audible cues to complete. The valve cannot be relocated to a more desirable location on the HUT because of lack of available real estate.

The risk associated with the position of the low flow purge valve prompted the investigation of alternative architectures including elimination of the high flow valve and relocation of the low flow valve to the place it previously occupied on the DCU. In this set up, the valve can remove gas from either the helmet, or the vent tree. The locations of the valves could be switched, with the low flow being located on the DCU and the high flow being located over the HUT shoulder. Finally, a single multi-position valve could be implemented on the DCU that is capable of flowing both high and low flow rates. The ideal configuration, however, would incorporate the use of a single position, low flow valve, for simplicity purposes, provided that configuration can meet both the CO_2 washout and nitrogen purge requirements.

The purpose of the analysis described in the document below is to reassess the architecture of the xEMU purge valve and determine the most optimal configuration in order to comply with xEMU requirements. Specifically, the analysis will focus on the possibility of functioning with a single low flow purge valve, as that configuration is ideal in concept.

II. Nitrogen Purge Analysis

A nitrogen purge analysis was conducted to determine the length of time required for the gas inside the xEMU to achieve a volume averaged composition of 95% oxygen prior initiating the remainder of the pre-EVA operations. A case matrix (see Table 1) was provided that required the investigation of different combinations of cabin environments, crewmember sizes, and pressurization setpoints to ensure that the purge did not take longer than 15 minutes under any conditions.

Before completing the provided case matrix (Table 1), the most optimal nitrogen purge routing configuration needed to be determined (Table 3). To accomplish this, the case that operated under the least favorable conditions for nitrogen purge was selected and run in ANSYS as a transient case, undergoing both pressurization, as well as the nitrogen purge sequence for accuracy. The specific conditions at which the model was initially run are as follows:

Table 1: xEMU Nitrogen Purge Case Matrix

Case Number	Cabin Conditions	Pressurization Setpoint (psid)	Suit Free Volume (ft3)
1	ISS	4.3	1.5
2	ISS	4.3	3.0
3	ISS	8.2	1.5
4	ISS	8.2	3.0
5	Exploration	4.3	1.5
6	Exploration	4.3	3.0
7	Exploration	8.2	1.5
8	Exploration	8.2	3.0

Note that the ISS cabin conditions are assumed to be 14.7 psia at 21% O2 and the Exploration cabin conditions are considered to be 8.3 psia at 34% O2 as specified by the analysis description.

- ~9 in^2 hatch membrane

- Ambient environment is set to ISS cabin conditions
- 3.0 ft^3 free volume in the PGS
- 0.19 ft^3 hatch free volume
- Suit pressurized to 4.3 psid over cabin
- Regulator setpoint during depress is 0.4 psid over cabin

The “worst case conditions” model described above was unable to purge the suit of nitrogen in under 15 minutes, so additional models and corresponding configurations where created to explore solutions to speeding up the purge time necessary to achieve 95% oxygen. The design modifications considered are as follows:

- Increasing the hatch membrane size
- Changing the primary regulator setpoint to 4.3 psid over cabin during purge
- The addition of a Zitex G-115 protected vent tree port in the hatch
- Decreasing the hatch free volume
- Turning on both the primary and secondary regulators at 4.3 psid over cabin during purge

A. Geometry and Model Construction

The xEMU Design Modeler geometry was adopted from a nominal CO_2 washout analysis[1] and altered to fit the needs of this analysis. Specifically, the hatch fluid volume, void of water bladders, tubing, and Trace Contaminant Control (TCC), was added to the preexisting xEMU model. A thin porous zone was positioned adjacent to the hatch to act as the semipermeable membrane. The viscous resistance of the porous zone was determined by constructing a simple tube model containing a 1 in^2 section of the membrane in ANSYS Fluent with which the Gurley test was conducted. The model was then run in ANSYS fluent iteratively under steady state conditions to calibrate the fan driving flow through the vent tree at 6 acfm. A parallelized User Defined Function (UDF) was written and compiled into the ANSYS model to calculate and control flow through the purge valve, which behaves as a long orifice with an L/D ~1.

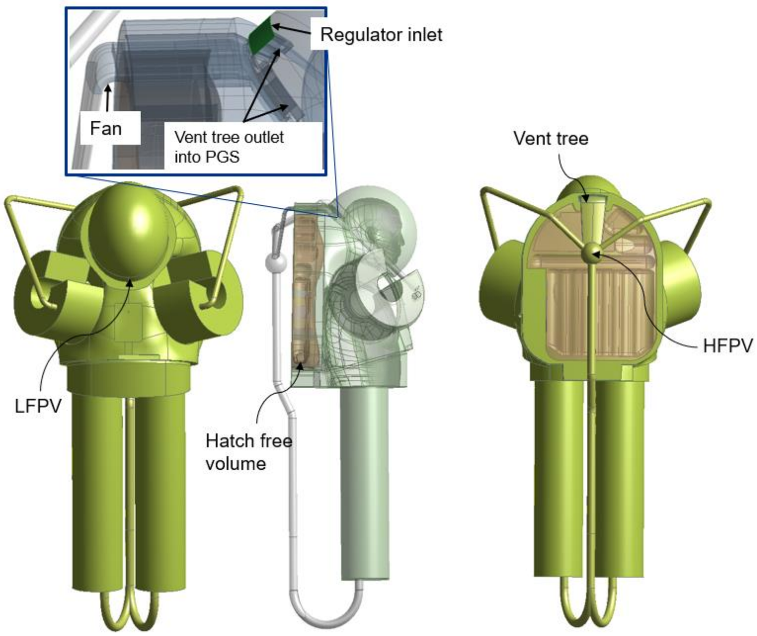


Figure 1: Nitrogen purge design modeler geometry

The equations of included in the UDF that govern the behavior of flow through the purge valve were derived from compressible flow equations [2,6]. It should be noted that the following series of equations used to calculate mass flow discharged from a long orifice is applicable to subsonic flow only.

The pressure ratio, r, is the ratio of the downstream pressure, P_{cabin}, to the upstream pressure, P_{suit}:

$$r = \frac{P_{cabin}}{P_{suit}} \tag{1}$$

The specific heat ratio of the fluid is given by γ:

$$\gamma = \frac{C_p}{C_v} \tag{2}$$

The Mach number, M_O, of the fluid traveling through the orifice is a function of both the pressure ratio and the specific heat ratio:

$$M_O = \sqrt{\frac{2}{\gamma-1}}\sqrt{r^{-\frac{\gamma-1}{\gamma}} - 1} \tag{3}$$

As mentioned above, the value of M_O must be less than one for these equations to be applicable. This condition is largely dominated by the critical pressure of the fluid. The critical pressure of any compressible fluid is the lowest pressure achieved at the region of the orifice with the smallest cross-sectional area for any given upstream pressure. When critical pressure is achieved, the flow becomes sonic. For diatomic gases such as oxygen and nitrogen, the ratio of critical pressure to upstream pressure is about 0.53, therefore any diatomic gas with a pressure ratio between 1 and 0.53 is in the subcritical region, where flow is subsonic, and the Mach number is less than 1.

The flow coefficient, C_{long}, which represents the fraction of actual flow through the orifice compared to that of isentropic flow through an ideal nozzle under the same conditions, is related to the pressure ratio for a long orifice with an L/D ratio of 1 by the following 5th order polynomial[3]:

$$C_{long} = 0.0401r^5 + 0.1359r^4 - 0.3401r^3 + 0.1092r^2 - 0.0166r + 0.9066 \quad (4)$$

The gas constant specific to any gaseous mixture, R_{gas}, is calculated by dividing the universal gas constant, R, by the molar mass, M, of the mixture:

$$R_{gas} = \frac{R}{M} \quad (5)$$

Finally, the mass flow rate, $\dot{m}$, of a compressible fluid through an orifice can be calculated using the following equation[6]:

$$\dot{m} = A_{orifice} C_{long} M_O P_{suit} \sqrt{\frac{\gamma}{R_{gas} T_{gas}}} \sqrt{r^{\frac{\gamma+1}{\gamma}}} \quad (6)$$

Where T_{gas} is the absolute temperature of the gas upstream, and $A_{orifice}$ is the open area of the orifice.

The PLSS specifications document[7] lists the capabilities of both the high and low flow purge valves from and upstream pressure of 3.7 psia to downstream vacuum (see Table 2). The mass flow rate through each purge valve under these conditions is cited as a range, so the lowest value for each range was used in order to produce a more conservative solution (smaller orifice open area, slower suit purges gas). The open area of the purge valve was calculated by implementing the flow rate provided in the PLSS specifications document into an excel spreadsheet programmed with the same compressible flow equations listed above. By inputting the upstream and downstream pressures, the Excel The Goal Seek Forecast plugin can be used to determine the open area of the orifice by adjusting its value until the cell containing the formula for mass flow rate through the orifice achieves its goal. Consequently, the diameter of the low flow orifice was determined to be 0.085in, and the diameter of the high flow orifice was determined to be 0.121 in.

Table 2: Open Loop Purge Flow (HV-314)

Position	Mass Flow Rate (pph)	Suit Pressure (psia)	Ambient Pressure	Suit Internal Temperature (°F)	Suit Internal Dewpoint[(4)] (°F)
OFF	~0[(1)]	---	---	---	---
LOW FLOW	1.55-1.69[(2)]	3.7	vacuum	60	negligible
HIGH FLOW	3.15-3.38[(3)]	3.7	vacuum	60	negligible

The compressible flow equations outlined above along with the calculated open area of the orifice were programmed into a compiled UDF within the ANSYS Fluent simulation. The UDF effectively mimicked subsonic transient flow behavior through a long orifice by looping over threads of cells in a specified zone within the mesh every iteration to gather parameter data such as temperature, density, and pressure and then implemented the collected variables into equation 6 to solve for mass flow rate. The calculated flow rate profile was then applied to a small cylindrical boundary extruded from either the neck ring or the vent tree.

B. Purge Architecture Configurations Considered

Details of the configurations considered can be found in Table 3 below. The 3rd column from the left describes the pressure of the suit at which the primary regulator is turned on. These configurations are included to investigate the effects of turning the regulator on as soon as the purge valve is pulled at 4.3 psid, rather than decompressing to 0.4 psid. This operational change should theoretically decrease purge time by inducing flow of pure oxygen into the suit sooner in the purging process. The 5th and 6th columns describe the free volume of the hatch, which is reduced from 0.19 ft^3 to 0.1 ft^3 in some configurations, and the size of the membrane connecting the PGS and hatch. By decreasing the free volume in the hatch, the space occupied by cabin gasses decreases as does the amount of nitrogen that needs to be removed from the hatch. Additionally, including configurations in which the hatch membrane size is increased so more flow can be exchanged with the PGS at any given time.

Table 3: Purge Architecture Configurations Considered

Case number	Cabin conditions	PGS pressurization setpoint (psid)	Primary regulator setpoint during purge (psid)	Suit free volume (ft^3)	Hatch free volume (ft^3)	Suit-to-hatch membrane size (in^2)	Hatch port area (in^2)	Purge valve type	Primary regulator mass flow rate (pph)	Secondary regulator set
1	ISS	4.3	0.4	3.0	0.19	9.45	N/A	High flow	4.24	OFF
2	ISS	4.3	0.4	3.0	0.19	18.2	N/A	High flow	4.25	OFF
3	ISS	4.3	4.3	3.0	0.19	9.45	N/A	High flow	15.13	OFF
4	ISS	4.3	4.3	3.0	0.19	9.45	4.9	Low flow	7.82	OFF
5	ISS	4.3	4.3	3.0	0.19	9.45	4.9	Low flow	6.0	OFF
6	ISS	4.3	4.3	3.0	0.19	9.45	4.9	Low flow	5.6	OFF
7	ISS	4.3	4.3	3.0	0.19	9.45	N/A	Low flow	5.6	OFF
7A	ISS	4.3	4.3	3.0	0.1	9.45	N/A	Low flow	5.6	OFF
8	ISS	4.3	4.3	3.0	0.1	9.45	N/A	Low flow	5.6	ON

Gases contained in the PGS volume are purged from the suit fairly efficiently because the purge valve pulls directly from that volume. However, in the baseline configuration the removal of nitrogen from the hatch is limited by the ability of fluids to diffuse across the hatch membrane. To increase the rate at which nitrogen is removed from the hatch, several configurations incorporate the use of an additional vent tree port that recirculates flow from the hatch.

The surface area of the port inside the hatch was determined using a combination of FloCAD and ANSYS software. In the FloCAD model (see figure 2), a set flow from the PGS to the hatch dictated the distribution of flow to the hatch vs the vent tree. The mass flow rate of the set flow into the hatch was the independent variable in this iterative process; the mass flow rate of the set flow connecting the suit free volume to the hatch free volume was adjusted in small increments until the time difference between the suit volume achieving 95% oxygen concentration and the hatch volume achieving the same concentration was ~ 1 minute. After the completion of the final iteration, the mass flow rate into the hatch was compared to the mass flow rate into the vent tree, to ensure that the vast majority of flow is recirculated from the suit rather than the hatch.

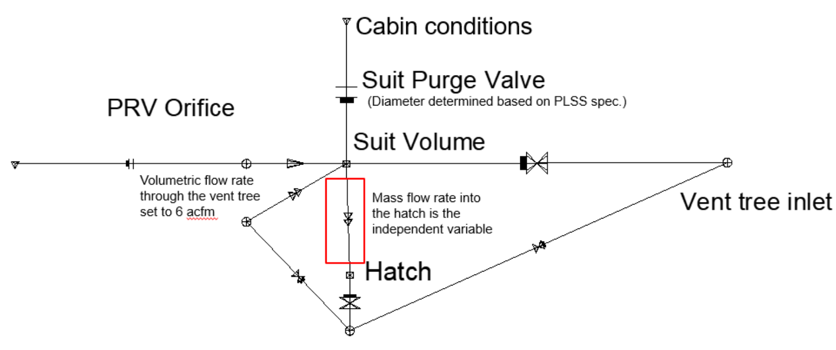


Figure 2: FloCAD model used to size the vent tree hatch port

In the event that 1.5 pph of gas is pulled from the port in the hatch, the average mass flow rate recirculating from the suit is 33.4 pph, therefore the hatch accounted for only 4.3% of the total recirculating flow into the vent tree, while the difference between the hatch volume and suit volumes achieving the desired oxygen content was a little less than a minute.

The hatch port was then sized using the same Gurley ANSYS model used to determine the membrane characteristics in conjunction with the pressure drop calculated between the inlet and outlet of the vent loop. The vent loop pressure drop is calculated as follows[7]:

$$\Delta P[in\ H2O] = 0.390 * ACFM^{1.860} * density^{1.860-1}[\frac{lbm}{ft3}] \quad (7)$$

The lowest volumetric flow rate and gas density entering the vent loop from the PGS achieved in the FloCAD model were used to calculate the vent loop pressure drop, as it produces the largest port size, and therefore is the most conservative option.

$$\Delta P = 0.390 * 5.07^{1.860} * 0.091^{1.860-1} = 1.01\ [in\ H_2O] \quad (8)$$

The mass flow rate at the inlet to the Gurley model was set to 1.5 pph, as determined to be an appropriate mass removal rate from the hatch by the FloCAD model, and the resistive properties of the porous zone remained the same as those determined in the initial Gurley test conducted previously. In order to determine the appropriate port size to allow for 1.5 pph of flow to leave the hatch, the porous membrane diameter was adjusted until the pressure drop across the membrane was equivalent to the calculated vent loop pressure drop. The required membrane area was found to be 4.91 in^2.

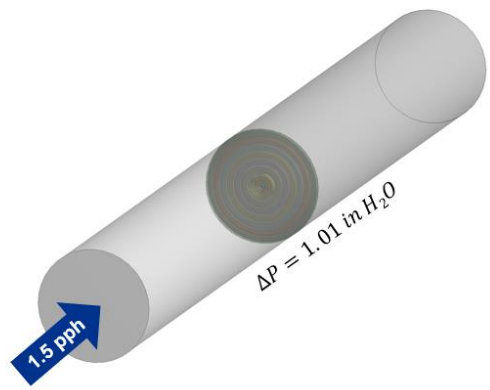


Figure 3: Gurley model altered to determine the necessary area of the hatch port

The final configuration considered incorporated the use of both the primary and secondary regulators to complete the purge. This operational change was considered in order to eliminate the decrease in suit pressure from 4.3 psid caused by the inability of the primary regulator to maintain the same flow rate as the purge valve when it is first opened. Increasing the flow rate of pure oxygen into the PGS, as well as maintaining a higher pressure differential between suit and cabin (resulting in a higher flow rate through the purge valve) was expected to result in a quicker purge time.

C. Analysis Results

The resulting time for the full suit in each configuration to achieve a volume averaged concentration of 95% O_2 can be found in Table 4 below:

Table 4: Results of Nitrogen Purge Analysis

Config. number	Cabin conditions	PGS pressure during purge (psia)	Primary regulator setpoint during purge (psid)	Suit free volume (ft^3)	Hatch free volume (ft^3)	Suit-to-hatch membrane size (in^2)	Hatch port area (in^2)	Purge valve type	Purge Time (min)	Primary regulator mass flow rate (pph)	Secondary regulator mass flow rate (pph)
1	ISS	15.1	0.4	3.0	0.19	9.45	N/A	High flow	>15 min*	4.24	OFF
2	ISS	15.1	0.4	3.0	0.19	18.2	N/A	High flow	12.9	4.25	OFF
3	ISS	19.0	4.3	3.0	0.19	9.45	N/A	High flow	4	15.13	OFF
4	ISS	19.0	4.3	3.0	0.19	9.45	4.9	Low flow	6.9	7.82	OFF
5	ISS	18.1	4.3	3.0	0.19	9.45	4.9	Low flow	7.9	6.0	OFF
6	ISS	17.7	4.3	3.0	0.19	9.45	4.9	Low flow	8.3	5.6	OFF
7	ISS	18.1	4.3	3.0	0.19	9.45	N/A	Low flow	11.9	5.6	OFF
7A	ISS	18.1	4.3	3.0	0.1	9.45	N/A	Low flow	10.3	5.6	OFF
8	ISS	18.9	4.3	3.0	0.1	9.45	N/A	Low flow	10.8	5.6	0.63

Cases 1-4, although valuable for providing insight into the weather or not the low flow valve could complete with the high flow valve in terms of purge time, are unrealistic for real world applications as no limitations were put on the primary regulator flow rate. In actuality, the primary regulator can flow no more than 6.0 pph, and the recommended operating maximum flow rate is 5.6 pph.

As can be seen from the relatively minimal differences in purge time between configurations 6 and 7 and cases 7 and 7A, the addition of the hatch port and reducing the hatch fluid free volume were found to be invaluable as solutions to lowering the nitrogen purge time due to the suit fluid volume dominating the average nitrogen concentration in the suit due to its larger volume. Despite there being a 3.6 minute difference in purge times between the configuration incorporating a vent tree port in the hatch (config. 6) and the otherwise equivalent configuration that doesn't (config. 7), implementation of the extra port in the hatch introduces the risk of the pressure difference between the hatch and vent tree causing the protective Zitex membrane to rupture, potentially allowing water from the FWSA to enter the vent loop.

Creating an operational change to set SOR=ON (secondary oxygen regulator) at 4.3 psid (config. 8), had a slightly adverse effect on the nitrogen purge time because there was no pressure differential across the hatch membrane, therefore the concentration of nitrogen in the hatch remained the same after pressurization. Despite the suit fluid largely dictating the volume weighted average nitrogen in the control volume, a consistently high nitrogen concentration in the hatch did slightly increase the purge time.

Table 5: Completed Nitrogen Purge Case Matrix

Case Number	Cabin Conditions	Pressurization Setpoint (psid)	Suit Free Volume (ft3)	Purge Time (min)
1	ISS	4.3	1.5	4.70
2	ISS	4.3	3.0	11.97
3	ISS	8.2	1.5	4.50
4	ISS	8.2	3.0	11.98
5	Exploration	4.3	1.5	3.86
6	Exploration	4.3	3.0	7.26
7	Exploration	8.2	1.5	3.50
8	Exploration	8.2	3.0	6.62

By comparing the purge times from the above configurations and weighing any potentially negative effects of implementing the changes, case 7 was determined to be the most optimal configuration considered and was therefore used to solve for the remainder of the case matrix (see Table 5).

Ultimately, all the cases completed using configuration 7 were able to purge the suit of nitrogen in under 15 minutes (the maximum allotted time for as specified in the analysis description), with the longest purge occurring over a period of 12 minutes. The results of this analysis confirm that the high flow purge valve is not needed to complete the nitrogen purge during the pre-EVA sequence, and that it can be completed by a low flow valve flowing from the helmet. This configuration was carried into the subsequent CO_2 washout analysis, which quantifies crewmember safety in emergency scenarios during which the intake of oxygen is compromised while on EVA.

Table 6: Results of 2016 xEMU Washout Analysis

Case	Purge Location	Metabolic Rate (Btu/hr)	Purge Flow Rate (lb/hr)	Average Inhaled PPCO2 mmHg
1	ventilation tree	400	1.7	7.68
2	ventilation tree	400	3.6	3.79
3	ventilation tree	800	1.7	15.06
4	ventilation tree	800	3.6	7.88
5	ventilation tree	1000	1.7	19.4
6	ventilation tree	1000	3.6	10.42
7	ventilation tree	1200	1.7	24.25
8	ventilation tree	1200	3.6	12.90
Case	**Purge Location**	**Metabolic Rate (Btu/hr)**	**Purge Flow Rate (lb/hr)**	**Average Inhaled PPCO2 mmHg**
1A	helmet	400	1.7	4.61
2A	helmet	400	3.6	2.38
3A	helmet	800	1.7	9.32
4A	helmet	800	3.6	4.88
5A	helmet	1000	1.7	11.14
6A	helmet	1000	3.6	6.34
7A	helmet	1200	1.7	12.62
8A	helmet	1200	3.6	7.82

III. Emergency Purge CO_2 Washout Analysis

In 2016, a CO_2 washout analysis[4] was completed for an earlier design iteration of the xEMU. The analysis examined helmet washout at metabolic rates ranging from 400-1200 BTU/hr for both the high and low flow valves removing fluid from the vent tree as well as the helmet. Ultimately the analysis concluded that purging at both flow rates, when flowing from the helmet, fell well within the 20 mmHg partial pressure (pp) of CO_2 restrictions, with the highest inhaled pp CO_2 being 12.6 mmHg in the case where the astronaut's metabolic rate was 1200 BTU/hr and the purge rate was 1.7 lb/hr (low flow). However, the cases in which the purge valve connected to the vent tree resulted in relatively high $ppCO_2$ inhalation when utilizing the low flow valve. Most of these cases, though higher in inhaled CO_2 than their helmet counterparts, remained within the safety limitations except for the case performed at 1200 BTU/hr with the low flow valve, which resulted in 24.25 mmHg CO_2 inhaled.

The CFD assessment confirmed that the low flow purge (1.7pph) could not meet the inspired PPCO2 limit of 20mmHg at 1200 BTU/hr and was marginal at 1000 BTU/hr when implemented into the vent loop. As a result, there was a push to split from a single Multi-position Suit Purge Valve (MSPV) located on the DCU but flowing from the vent tree, to a high flow purge valve located on the DCU (pulling from the ventilation tree) and a low flow purge valve on the helmet. The separate valves were implemented, however, due to the real-estate available on the HUT, has elected to place the purge valve in a location that is over the crewmember's right shoulder and is both single hand access only (right hand only) and a blind operation reliant upon audible verification.

Due to the results from the nitrogen purge analysis (described in the sections above) confirming that the low flow valve is capable of removing nitrogen from the suit in a timely manner, there has recently been interest in removal of the high flow valve entirely, relying solely on the use of a single low flow helmet purge valve. This analysis that will be discussed in the sections to come will discuss the viability of this option.

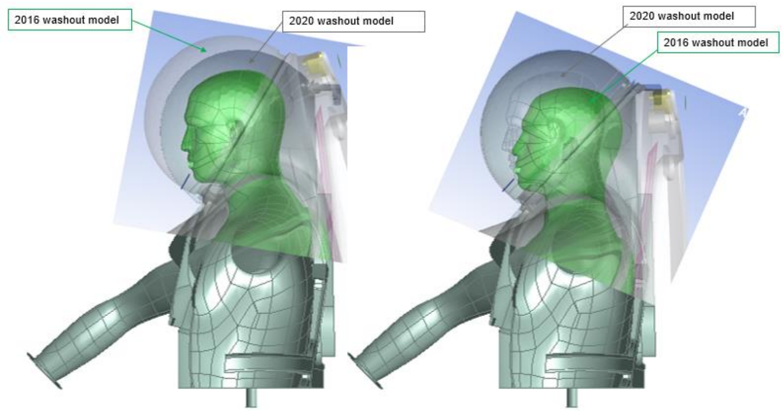
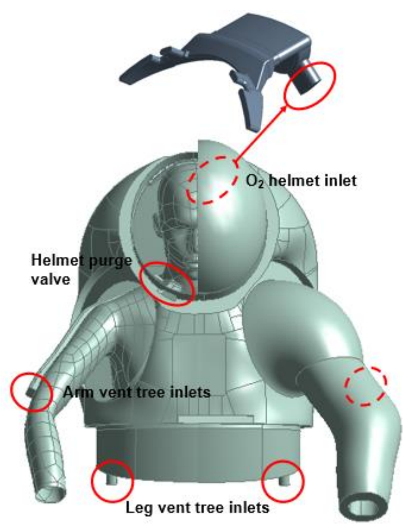


Figure 4: Comparison of crewmember head position before and after configuration changes.

A. Geometry and Model Construction

Since the completion of the 2016 washout analysis, there have been numerous changes made to the xEMU design resulting in updates being made to the model geometry. These alterations include the changes in the hydraulic diameter of the oxygen inlet, the number of inlets to the purge valve, and suit configuration changes that caused changes to the position of the suited crewmember. Changes to the hydraulic diameter of the oxygen inlet in the helmet were made to address pressure drop and ventilation noise issues. The purge valve design was updated in the model, as it had not been available to be incorporated into the 2016 version of the model, so a single straw-like geometry had been used rather than the multiple converging inlet port design that was used for this analysis. Although this model yielded favorable results, the location of the purge valve (directly on the helmet bubble in front of face) was unrealistic, so consideration was not given to that design in the updated analysis.



Boundary	Helmet Purge	Vent Tree Purge
Vent tree inlet (arms)	Wall	Pressure outlet
Vent tree inlet (legs)	Pressure inlet	Pressure outlet
Helmet purge valve	Velocity outlet	Wall
O_2 helmet inlet	Velocity inlet	Mass flow inlet set to purge flow rate

Figure 5: Model boundary conditions in either purge scenario

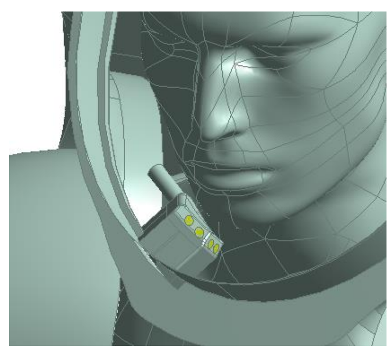


Figure 6: Case 1 purge valve

Updates to the suit geometry result in the astronaut being in a more erect, comfortable position. An unintended effect of these changes was the crewmember's mouth being positioned closer to the helmet bubble wall and his head, overall, being positioned higher in the suit (see figure 4). The image on the right side depicts the change in crewmember position, while the image on the left verifies that the size of the astronaut's head is the equivalent between models. In the 2016 model (green), there is sufficient space between the crown of the crewmember's head and the oxygen inlet to allow for flow to wash over the top of the head undisturbed. Additionally, the positioning of the mouth further from the bubble wall ensures that less metabolic waste will rebound off the bubble with enough momentum for the astronaut to inhale it in the next breathing cycle. All aspects considered, the position of the crewmember without these configuration changes, is theoretically preferential for washout purposes.

It should be noted that the size and position of the head inside of the helmet is expected to affect the washout results, therefore a sensitivity analysis would need to be conducted to examine the extent of the tolerance created by these considerations; the size and position considered in this analysis is a baseline.

Unlike the nitrogen purge model, the breathing of the astronaut is incorporated into the washout model via a UDF originally created by Moses Navarro[1] to model human metabolic rates. In this analysis, a metabolic rate of 1200 BTU/hr and a breathing period of 2.85 seconds was assumed. In short, the UDF loops over threads of cells adjacent to the mouth of the crewmember and communicated to that boundary the composition of gases to inhale. CO_2 and H_2O contribution as well as oxygen consumed while in the virtual lungs was calculated in a mass balance based on the metabolic rate. The calculated metabolic waste and leftover oxygen are then discharged from the mouth boundary at core temperature. The argument of the breathing sine wave, or rather the discharge velocity of the gases, was taken from data presented in the Bioastronautics Data Book[5].

The waist boundary of the model was set to a pressure outlet to both account for flow into the PGS legs as well as stabilize the suit pressure. Pressure stabilization is necessary because both the oxygen inlet boundary and the purge valve outlet maintain a constant velocity condition (see figure 6), which in conjunction with the crewmember's removal of mass from the suit by breathing, causes the suit pressure to drift from the desired 3.5 psid over vacuum. The pressure outlet utilizes a newly incorporated macro in the UDF to calculate the average concentration of each gas leaving the suit over an exhale period, and updates the species entering the waist boundary during an inhale period based on that data.

B. Model Results and Modifications

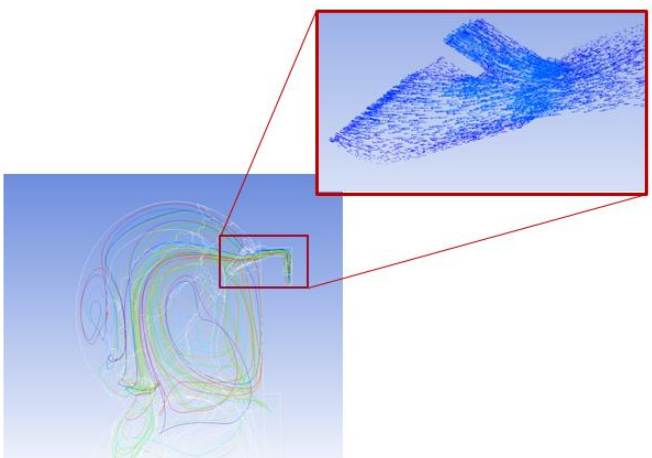


Figure 7: Resulting flow field from case 1

The model was initially run with the oxygen inlet pictured in Figure 5, and the purge valve (pictured in Figure 6) shifted 1.5 in circumferentially around the neck ring from its original intended position, such that it was positioned closer to the mouth. This configuration failed to meet requirements, with the average inhaled partial pressure of CO_2 being 21.56 mmHg.

Examination of post processing plots (Figure 7) revealed that the majority of the inlet flow traveled around either side of the head, rather than over the top which theoretically pushes the CO_2 away from the mouth area before inhale. The orientation of the inlet flow was suspected to be caused by the horizontal approach velocity superimposed by the geometry. Despite the oxygen ports being angled upward to direct the flow in the direction of the bubble wall, the momentum of the flow is horizonal, as is the ejected velocity vector.

In an attempt to change the momentum vector and therefore the direction of the inlet flow, case 2 incorporated an inlet design in which the inlet geometry was created by extruding the port surface at an angle such that the velocity inlet boundary condition exists on the same vector as that normal to the port surface (Figure 8). The case 2 configuration resulted in a similar inhaled $ppCO_2$ to that of case 1. This phenomenon appeared to have been caused by the introduction of vortices behind the head caused by increased flow friction within the boundary layer, a fact that became evident upon examining the local skin friction. Skin friction is defined as the ratio between local sheer stress and dynamic pressure. The skin friction (Figure 9) is visibly higher in the region where the inlet streamlines collide with the bubble wall. The friction in the region could be reduced either by decreasing the inlet velocity or by decreasing the angle of the vent.

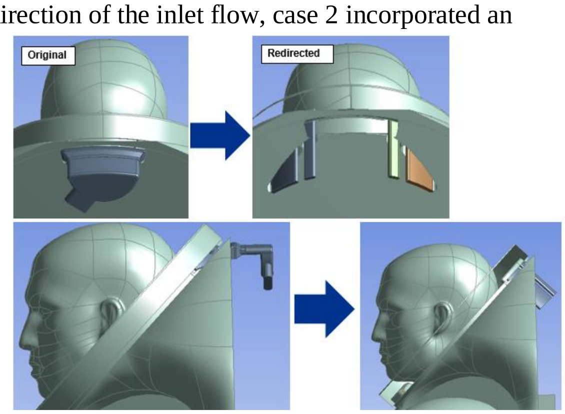


Figure 8: Redirected inlet geometry in case 2

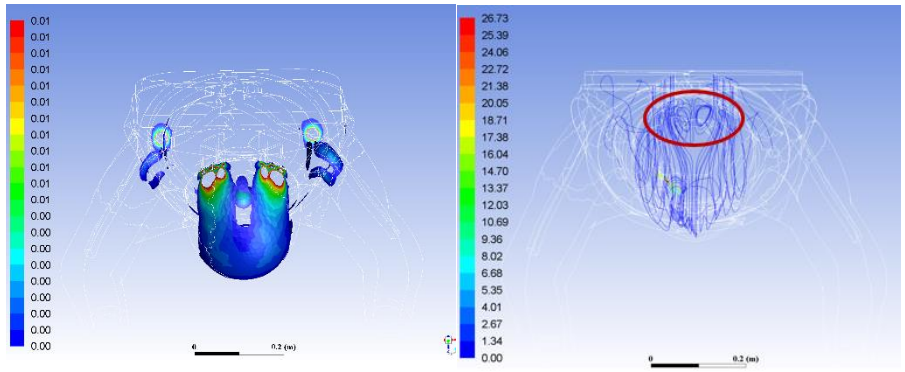


Figure 9: Local skin friction contour and streamlines for case 2

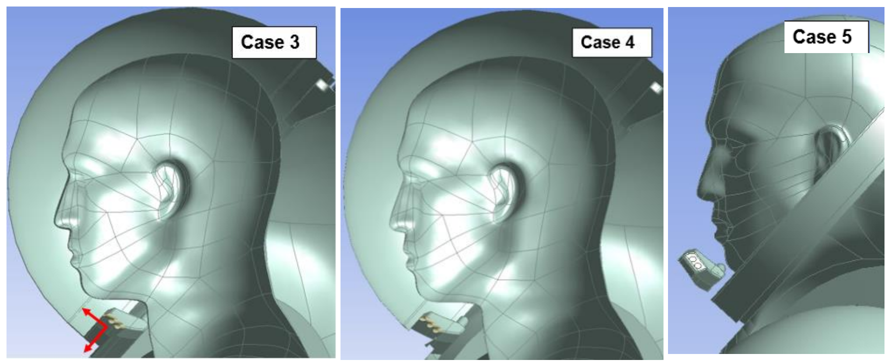


Figure 10: Position of the purge valve in cases 3-5

Cases 3-5 then examined the effects of changing the position of the purge valve relative to the mouth. The valve was moved circumferentially along the neck ring in all 3 cases (3, 4, and 5) such that it is positioned directly under the crewmember's chin. The difference between case 3 and 4 is that in case 4 the valve is moved closer to the neck ring than in case 3 and is moved up closer to the apex of the chin (Figure 10). The purge valve is case 5 is positioned unrealistically close to the mouth, protruding from the helmet bubble. The purpose of conducting this case is to determine if there is any position of the valve geometry that would result is adequate washout, the thought being that if we can't meet the inhaled CO_2 requirement with it in this "best case" location, then another element of the design needs to change, possibly in conjunction with the valve position.

Case 3 failed to meet the inhaled CO_2 requirements, while case 4 passed by a slim margin and case 5 saw greater success (see Table 7 for a summary of washout results). Ultimately this sensitivity analysis reveals that the closer the purge valve is to the crewmember's mouth, the better washout is. However, safety during an emergency scenario cannot rely on the position of the valve relative to the mouth given that the crewmember's head will inevitably move.

Table 7: Summary of Washout Results

Case number	Alteration type	Met. rate (BTU/hr)	Flow rate (pph)	Inspired $ppCO_2$ (mmHg)
Case 1	1.5" circumferentially C.C.W	1200	1.7	21.57
Case 2	Redirected inlet vent	1200	1.7	21.98
Case 3	Under chin: position 1	1200	1.7	21
Case 4	Under chin: position 2	1200	1.7	19.75
Case 5	Under mouth	1200	1.7	14.2

A variety of oxygen inlets were examined in the cases that followed. To ensure that there was no change in pressure drop to the system, the total surface area of the ports in the first two designs remained the same as in the

Figure 11: Inlet designs considered

original geometry provided. In case 6, the outer ports and inner ports are switched such that the larger ports are closer to the crown of the head and the smaller ports closer to the sides. A little area is removed from the inner ports in case 7 to create a 3rd port that distributes flow over the top of the head. See figure 11 above for depictions of the designs.

Both designs failed to meet the inspired CO_2 requirement with an acceptable margin (aiming to achieve ~15 mmHg pp CO_2 to ensure safety if the situation varies in height, head position and size, etc. from the model). Case 6 resulted in >20.7 mmHg pp CO_2, although the run was stopped before it could achieve steady state, so the exact solution is unknown. Case 7 produced a similar 19.9 mmHg ppCO_2. Examination of post processing videos displaying iso-surfaces mapping specific concentrations of CO_2 reveal that the exhaled breaths are dispersing over the crewmember's face, rather than being pushed down into the HUT and removed by the purge valve. This behavior can be seen in the CO_2 concentration contour to the left; the image is taken at the peak velocity of an inhale (halfway through an inhale period) and reveals that the cloud of metabolic waste produced during the previous exhale is fairly spread out over the lower half of the crewmember's face, the resulting in his/her inhaling a high concentration of CO_2.

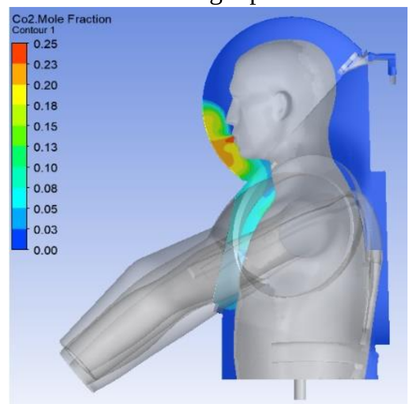


Figure 12: Contour of concentration of CO_2 at the bisectional suit plane

IV. Conclusions and Current Work

The analyses described in the paper above examined the purging capabilities of the xEMU if the high flow purge valve were to be removed and both the nitrogen and emergency purges were to be performed with a low flow valve instead. Part II of this paper focuses solely on the models created to imitate the pre-EVA nitrogen purging scenario. By considering a variety of design and operational changes, it was concluded that the low flow valve was capable of removing nitrogen from both the PGS and the hatch in a timely manner if the primary regulator pressure set point was increased from 0.4 psid to 4.3 psid. By incorporating this operational change into the purge procedure, potentially invasive design modifications could be avoided.

Although the performance of a single low flow helmet purge valve was deemed acceptable in the case of completing the pre-EVA nitrogen purge, we have yet to prove if it can achieve the necessary CO_2 washout requirements during emergency scenarios on EVA. To date, a few different inlet designs have been simulated in the washout model as well as a variety of purge valve locations. The most recent design iterations incorporated a reduction in the oxygen inlet port area, as it is expected that the exhaled metabolic waste cloud will be pushed down into the HUT cavity away from the mouth if the discharge velocity was higher. These analyses also included the newest purge valve design iteration. The analyses were conducted with a 20% and 50% reduction in port area but have yet to meet the necessary requirements.

After an adequate solution(s) is achieved through simulation, recommendations for several inlets will be made to include in washout testing; this testing will further validate the solution as well as the model and provide insight into the margin of error to expect from this particular model in the future.

Efforts to eliminate the high purge valve from the xEMU design continue, in order to minimize room for error and to make the suit as safe as possible for those who use them.

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[7] NASA JSC, "Subsystem Specification for the Exploration EMU (xEMU) Portable Life Support Subsystem (PLSS)", Engineering Directorate Crew and Thermal Systems Division, pg. 121, [R.PLSS.300.047] Open Loop Purge Flow (HV-314), 27 September 2018.