

Space Suit CO₂ Washout During Intravehicular Activity

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Nomenclature

ACES	Advanced Crew Escape System
acfm	Actual Cubic Feet per Minute
Btu	British Thermal Units
CDC	Center for Disease Control
CFD	Computational Fluid Dynamics
cfm	Cubic Feet per Minute
CO ₂	Carbon Dioxide
CSSE	Constellation Space Suit Element
CTSD	Crew and Thermal Systems Division – JSC
CxP	Constellation Program
EVA	Extravehicular Activity
ECLSS	Environmental Controls and Life Support System
EDAC	EVA Design Analysis Cycle
EMU	Extravehicular Mobility Unit
ESPO	EVA Systems Project Office
H ₂ O	Water
hr	Hour(s)
HSIR	Human Systems Integration Requirements
in.	Inch(es)
IRMA	Integrated Risk Management Application
IVA	Intravehicular Activity
JSC	Johnson Space Center
LEA	Launch/Entry/Abort
mmHg	Millimeters of Mercury
NIOSH	National Institute of Occupational Safety and Health
O ₂	Oxygen
OSHA	Occupational Safety and Health Administration
p/f	Pass/Fail
PGS	Pressure Garment Subsystem
psia	Pounds per Square Inch Absolute
SE&I	Systems Engineering and Integration
SME	Subject Matter Expert

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I. Introduction

Space suit carbon dioxide (CO₂) washout refers to the removal of CO₂ gas from the oral-nasal area of a suited astronaut's (or crewmember's) helmet using the suit's ventilation system. Inadequate washout of gases can result in diminished mental/cognitive abilities as well as headaches and lightheadedness. In addition to general discomfort, these ailments can impair an astronaut's ability to perform mission-critical tasks ranging from flying the space vehicle to performing lunar extravehicular activities (EVAs).

During design development for NASA's Constellation Program (CxP), conflicting requirements arose between the volume of air flow that the new Orion manned space vehicle is allocated to provide to the suited crewmember and the amount of air required to achieve CO₂ washout in a space suit. Historically, space suits receive 6.0 actual cubic feet per minute (acfm) of air flow, which has adequately washed out CO₂ for EVAs. For CxP, the Orion vehicle will provide 4.5 acfm of air flow to the suit. A group of subject matter experts (SMEs) among the EVA Systems community came to an early consensus that 4.5 acfm may be acceptable for low metabolic rate activities. However, this value appears very risky for high metabolic rates, hence the need for further analysis and testing.

An analysis was performed to validate the 4.5 acfm value and to determine if adequate CO₂ washout can be achieved with the new suit helmet design concepts. The analysis included computational fluid dynamic (CFD) modeling cases, which modeled the air flow and breathing characteristics of a human wearing suit helmets. Helmet testing was performed at the National Institute of Occupational Safety and Health (NIOSH) in Pittsburgh, Pennsylvania, to provide a gross-level validation of the CFD models. Although there was not a direct data correlation between the helmet testing and the CFD modeling, the testing data showed trends that are very similar to the CFD modeling. Overall, the analysis yielded results that were better than anticipated, with a few unexpected findings that could not easily be explained. Results indicate that 4.5 acfm is acceptable for CO₂ washout and helmet design. This paper summarizes the results of this CO₂ washout study.

II. Purpose

The purpose of this paper is to document a study that characterized CO₂ washout performance of space suit helmets. The objective of this study was to validate an air flow rate of 4.5 acfm from the Orion ECLSS suit loop as acceptable to provide adequate CO₂ washout to the crew during Orion suited intravehicular activities (IVAs). CFD modeling and suit helmet testing were performed in order to validate the flow rate. Based on the data acquired, this paper presents a recommendation to accept the 4.5 acfm flow rate from the suit loop.

III. Background

Adequate removal of CO₂ from within the suit depends largely on helmet design and volumetric air flow of the breathing gas coming into the suit via the helmet. Historically, the EVA community has been comfortable with 6.0 acfm of air flow and subsequently designed helmets to work with that flow rate. Under CxP direction, the Orion Project is designing a suit ventilation loop that will provide 4.5 acfm of breathing air to the suit. Many within the program believed that this would be sufficient since the application is for low metabolic rate IVA-type activities such as flying the vehicle or reconfiguring the cabin throughout the different mission phases in both a pressurized and unpressurized cabin. Designing a suit loop that can support the proven 6.0 acfm of breathing air incurs a significant increase in mass and power consumption that the Orion vehicle cannot handle. Conversely, NASA has never built a space suit helmet to operate at 4.5 acfm, and at the beginning of this study, there was concern that adequate CO₂ washout could not be attained with this flow rate. The CO₂ washout study was initiated in January 2009 to assess at a high level the feasibility of using the 4.5 acfm flow rate with helmets that represent the current Constellation Space Suit Element reference architecture.

III. Assumptions

The following assumptions were used throughout this analysis:

Assume launch/entry/abort (LEA) scenarios where the crew will see 14.7 pounds per square inch absolute (psia) of ambient air pressure within the cabin plus approximately 0.5 psia vent pressure within the suit.

Assume an unpressurized cabin survival scenario in which the suit will be pressurized to 4.3 psia.

Assume metabolic rates of 800 British thermal units per hour (Btu/hr) to represent the crewmembers in a resting state during launch and reentry, as well as 1600 Btu/hr to represent crewmembers under high stress during an abort or other off-nominal scenario.

Assume space suit helmets will be used that are derived from the CxP EVA technical baseline. This includes the following:

- A Mark III-based conformal helmet that isolates the volume immediately in front of the face for air flow and CO₂ washout.
- The U.S. Air Force S1034 helmet – A variant of the Space Shuttle Advanced Crew Escape Suit (ACES) helmet that is currently in service and also incorporates the isolated face-volume concept.
- The Mark III hemispherical helmet in its original open configuration – This provides a basis of comparison for CO₂ washout data. Comparing this data against the conformal helmet provides a good look at the common helmet concept that is part of the technical baseline.

IV. Technical Approach

Two phases of the study occurred from January to October 2009. For phase one, the analysis team consisted of the lead analyst and thermal analysts who solicited subject matter expertise to perform a subjective evaluation of the CO₂ washout issue. Phase two called for the analysis team to quantify the phase one conclusions using CFD analysis and hardware testing.

A. Phase One: Subjective Consensus and Evaluation

Phase one consisted of discussion sessions with EVA SMEs to discuss the feasibility of using an air flow rate of 4.5 acfm to provide adequate CO₂ washout in a space suit. Representatives within the EVA community - the EVA Systems Project Office (ESPO) chief engineer, Pressure Garment Subsystem (PGS) SMEs, and thermal analysis SMEs - as well as representatives from the space medicine community participated in this discussion. The basic conclusions were as follows:

- 4.5 acfm might be acceptable for CO₂ washout during low metabolic rate activities.
- 4.5 acfm is a risk during high metabolic rate activities such as the LEA phases of a flight.

Regardless of the flow rate, helmet design is a significant factor to providing proper CO₂ washout.

Phase one ended with the decision to continue this analysis as phase two follow-on task by quantifying the conclusions drawn thus far.

B. Phase Two: Quantifying CO₂ Washout

Phase two of this study characterized CO₂ washout performance using the three helmet configurations previously discussed. The thermal analysis consisted of CFD modeling to run the LEA and unpressurized cabin scenarios. Shortly thereafter, helmet testing with a mechanical breathing apparatus provided both a set of data points to characterize performance as well as a means of validating the CFD models.

Test and analysis runs were considered successful by the analysis team if the average partial pressure of CO₂ that was breathed in by the human measured less than 7.6 mmHg. This value was derived from legacy Extravehicular Mobility Unit (EMU) suit requirements and CxP 70024, *Constellation Program Human Systems Integration Requirements* (referred to herein as “HSIR”). The space medicine community at Johnson Space Center (JSC) disagreed with the analysis team regarding the interpretation of the CO₂ washout requirement, maintaining that the success criterion should be less than 5.0 mmHg instead of 7.6 mmHg. The analysis team did not resolve this discrepancy during the study and carried both success criteria as part of the results.

1. CFD Modeling

The CFD cases began with the most conservative parameters while holding the air flow as a constant at 4.5 acfm. The inlet air flow assumed 2.3 mmHg partial pressure of CO₂ injected into the line to represent the maximum nominal CO₂ that will flow into the helmet from the suit loop. The metabolic rate was set at 1600 Btu/hr, which represents the metabolic rate of the crewmember when dealing with launch loads and vibration, as well as a high-stress contingency scenario. As the analysis progressed, the parameters were changed to acquire more data points to characterize helmet air flow; however, these initial parameters were of the greatest interest to this analysis.

The analysis team ran cases at 3.0, 5.0, and 6.0 acfm to characterize alternative flow rates to the 4.5-acfm value that was established. The value of 3.0 acfm represents a target flow rate the Orion vehicle may be able to provide in the suit loop and still meet mass and power constraints. Values of 5.0 and 6.0 acfm represent possible flow rate options if the 4.5 acfm value is deemed inadequate. All of the runs maintained 2.3 mmHg of CO₂ injected into the helmet.

Mark III Conformal Helmet with Occupant Protection

The Mark III conformal helmet with occupant protection represents the helmet concept that is closest to the EVA reference architecture. It combines the bubble-shaped hemispherical Mark III helmet with the occupant protection inserts, face dam, and a multi-hole spray bar that blows air into the helmet similar to the U.S. Air Force S1034 helmet. This face dam concept partitions the volume of space in front of the face from the rest of the head as the air flow volume of interest for breathing and suit air flow. Air flows into the helmet from 16 inlet holes in a spray bar across the top of the helmet bubble (above the eyes), and out of the helmet through an outlet port that is 3 inches (in.) long and 1/2-in. wide (in front of the chin). See Fig. 1 and Fig. 2.

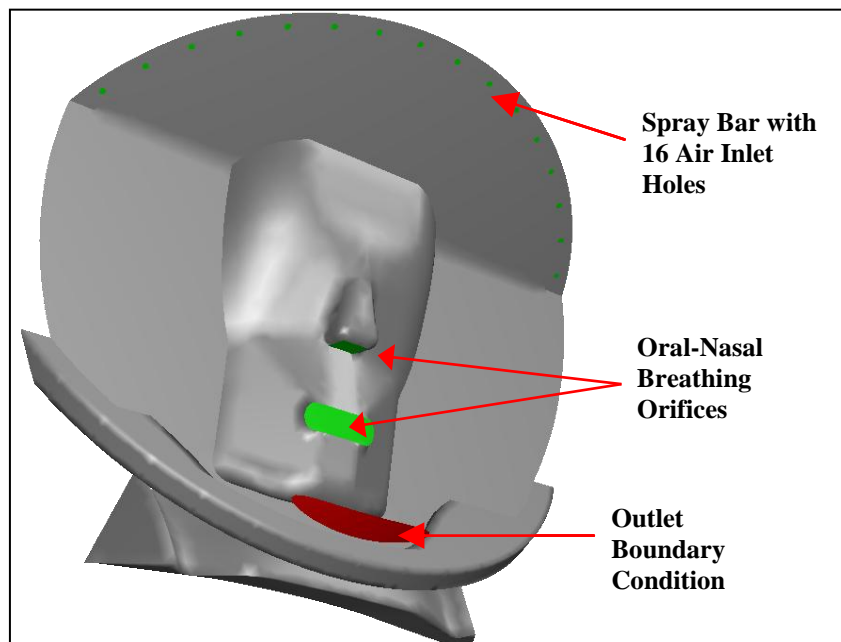


Figure 1. Boundary conditions of Mark III conformal helmet with occupant protection.

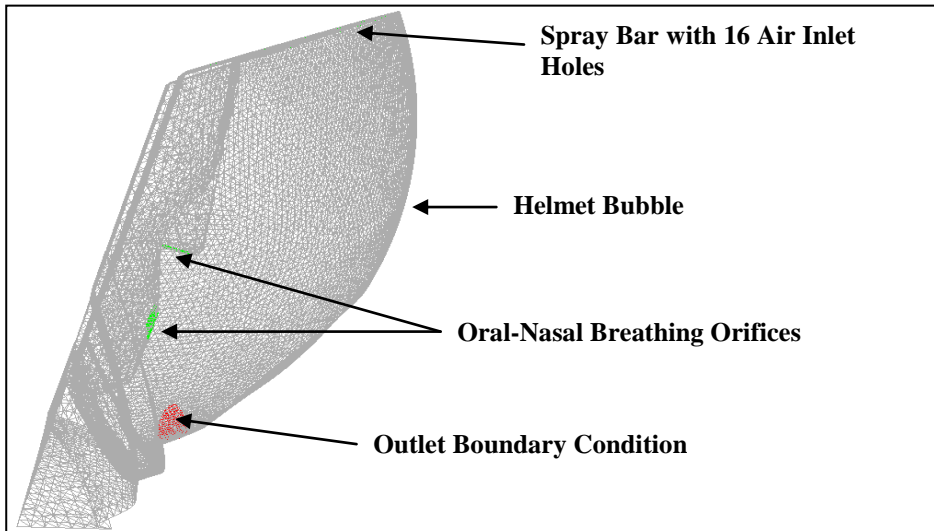


Figure 2. Profile of Mark III conformal helmet with occupant protection.

Mark III Open Helmet

The Mark III open helmet represents a hemispherical open-helmet configuration that includes air volume around the head and neck as the air flow volume of interest. See Fig. 3. Air flows into the helmet from an inlet just above the head that measures 3 in. by 1/2 in. and flows past the neck region and out through the upper torso of the suited crewmember. See Fig. 4.

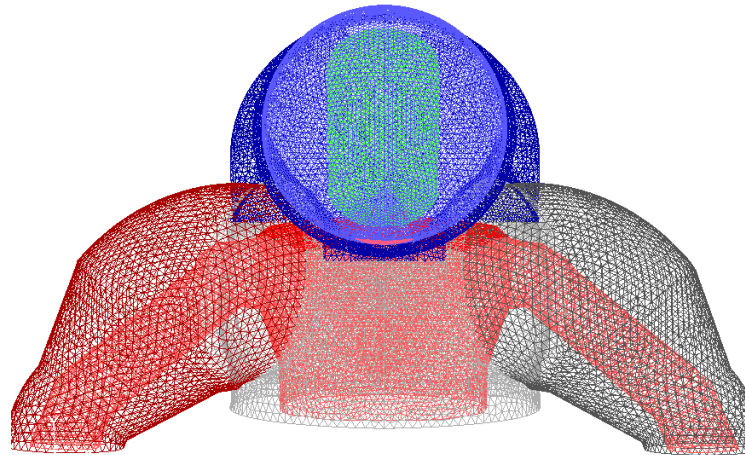


Figure 3. Front view of Mark III open helmet model.

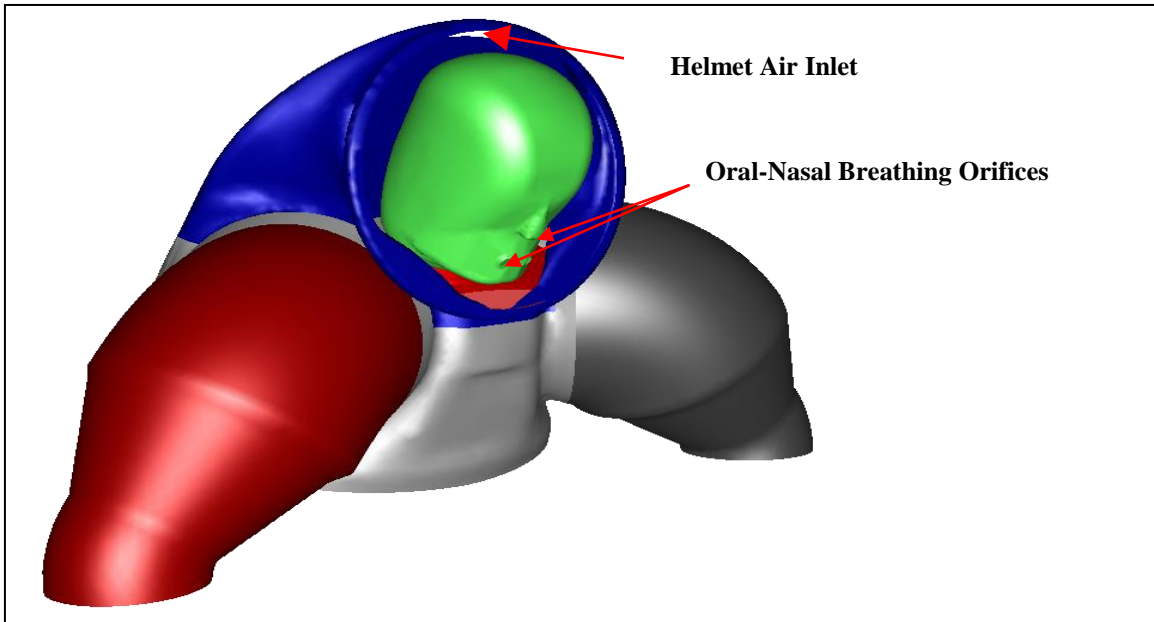


Figure 4. Oblique view of Mark III open helmet model.

U.S. Air Force S1034 Helmet

The U.S. Air Force S1034 helmet represents an isolated facial volume helmet that is currently in service. See Fig. 5. The actual helmet operates as a demand breathing system with a demand regulator and a check valve at the breathing outlet that allows the flow of air in and out of the helmet each time the crewmember takes a breath. For CFD purposes, the model functions as a continuous air flow helmet. Air flows into the helmet through inlet air holes located along the perimeter of the helmet-visor interface and flows out of a single round opening near the chin of the head form. See Fig. 6.

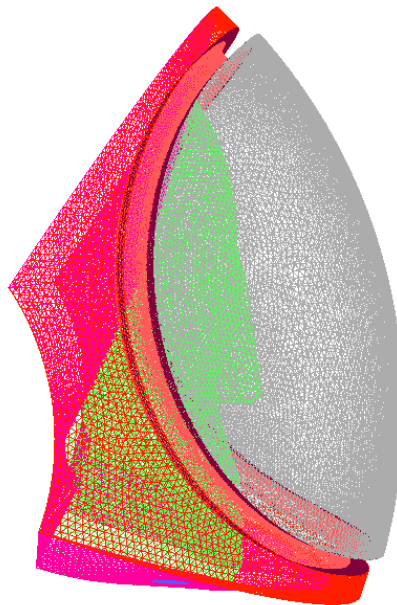


Figure 5. Side view of U.S. Air Force S1034 helmet model.

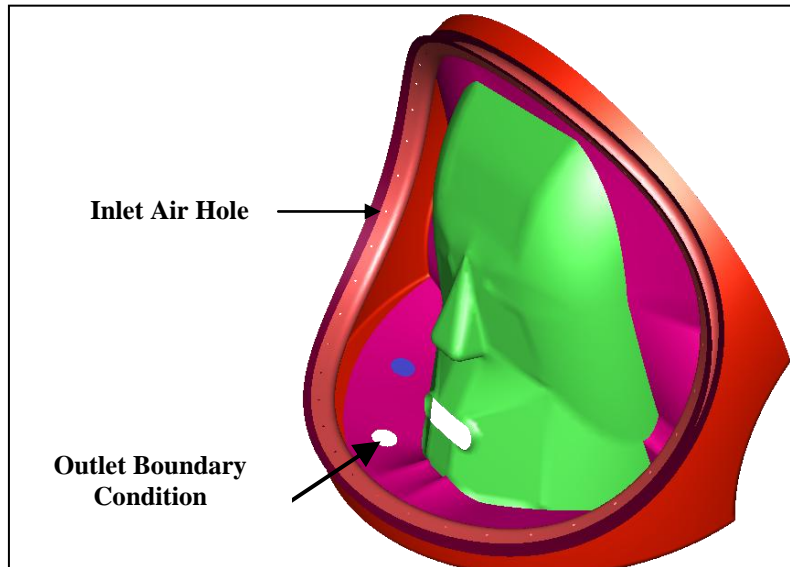


Figure 6. Inlet and outlet of U.S. Air Force S1034 helmet model.

CFD Results

The analysis team expected the low-volume helmet concepts (i.e., the U.S. Air Force S1034 helmet and the Mark III conformal helmet) to perform very well. The rationale was that a smaller volume of air would allow for less fresh air to mix with CO₂ and more concentrated flow out of the helmet. In reality, the CFD modeling showed no consistent trends between the low-volume helmets and the higher-volume Mark III open configuration helmet. See Table 1.

The 3.0 acfm cases generally performed well against the EVA success criteria, but not as well against the space medicine limit. The Mark III conformal helmet that represented the EVA reference architecture helmet failed the highest risk case - the high-metabolic rate launch/entry case - based on both success criteria. The Mark III open configuration helmet performed generally well at 3.0 acfm, but S1034 helmet did not. Given the variability of the 3.0 acfm analysis results and the difference in success criteria, the analysis team does not recommend changing the Orion suit loop flow rate to 3.0 acfm.

At 4.5 acfm, the Mark III open configuration helmet consistently performed better than the Mark III conformal helmet. Both helmets exhibited diminished performance at high metabolic rates of 1600 Btu/hr, as expected. The Mark III conformal helmet failed both the EVA and the Space Medicine success criteria during the high-metabolic launch/entry case and almost failed both criteria during the high-metabolic unpressurized cabin scenario. The Mark III open configuration helmet passed the EVA success criterion for the high-metabolic case and then passed both success criteria for the high-metabolic unpressurized cabin scenario. Both helmet configurations performed fairly well at 4.5 acfm during the low-metabolic rate cases. The S1034 helmet performed similarly to the Mark III open configuration helmet. It passed the EVA success criterion for the high-metabolic rate launch/entry cases at 4.5 acfm.

The 5.0 and 6.0 acfm models yielded some unexpected mixed results that could not be readily explained. For the high-metabolic rate cases, the CO₂ washout predictably improved as the suit loop flow rate increased. The S1034 helmet passed both success criteria for the low-metabolic launch/entry cases at 5.0 and 6.0 acfm. However, for the launch/entry Mark III open configuration cases, the CO₂ washout actually worsened as the flow rate increased. This result is also seen in some of the helmet testing performed at the NIOSH, and in both cases, the analysis team was not able to explain this occurrence. Without an explanation for this, the team did not have enough data to justify a recommendation to increase the suit loop air flow from 4.5 acfm.

The analysis results emphasized the importance of a proper helmet design to attain adequate CO₂ washout. The low-volume helmet concepts did not perform consistently well, but the open configuration helmet performed better than expected. Overall, 4.5 acfm proved to be an attainable flow rate to properly washout CO₂. Thus, based on the CFD models, the team recommends accepting 4.5 acfm for an Orion suit loop flow rate.

Table 1. CFD analysis results.

Model	Mark III Conformal Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
	800				1600				800				1600			
Met Rate (BTU/hr)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	6.9	5.2	4.8	4.2	11.6	8.2	7.4	6.2	4.8	4.6	4.4	3.9	7.5	7.3	6.8	5.8

Model	Mark III Open Configuration Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
	800				1600				800				1600			
Met Rate (BTU/hr)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	4.5	3.8	3.9	4.3	6.7	5.3	5.5	6.2	3.6	3.3	3.3	3.3	5.3	4.6	4.4	4.3

Model	United States Air Force S1034 Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
	800				1600				800				1600			
Met Rate (BTU/hr)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	5.6	3.7	3.4	2.8	9.1	5.3	4.6	3.4	5.4	3.2	3.3	2.9	9.2	4.5	4.2	3.2

	Test point passes both the Space Medicine and EVA pass/fail (p/f) criteria of 5.0 mmHg and 7.6 mmHg average inhaled ppCO₂.
	Test point fails the Space Medicine p/f criterion of 5.0 mmHg average inhaled ppCO₂, but passes the EVA p/f criterion of 7.6 mmHg.
	Test point fails both the Space Medicine and EVA p/f criteria of 5.0 mmHg and 7.6 mmHg average inhaled ppCO₂.

2. Helmet Testing at the NIOSH

As a means of validating the CFD data, the analysis team performed testing to characterize CO₂ washout performance using helmets that are similar in configuration to the CFD models. NIOSH offered a metabolic breathing instrument in Pittsburgh, Pennsylvania to perform this testing. The test data indicated many of the same trends that the CFD analysis showed, providing a gross-level validation of the CFD analysis. The analysis team performed additional tests on variations of the Mark III helmet configurations to characterize the performance of different helmet features.

The helmet testing incorporated the same test parameters used during the CFD analysis work. The team ran the inlet air flow at 3.0, 4.5, and 6.0 cubic feet per minute (cfm) assuming both low- and high-metabolic rates of 800 and 1600 Btu/hr. Some test cases included CO₂ injected into the inlet at a partial pressure of 2.3 mmHg to represent the maximum allowable CO₂ into the suit vent loop.

NIOSH Overview

NIOSH is a federal agency under the Centers for Disease Control (CDC) whose objective is to research and provide recommendations for preventing workplace injuries and illnesses. This differs from the Occupational Safety and Health Administration (OSHA) because OSHA is a Department of Labor agency that is responsible for enforcing workplace safety regulations and practices. The NIOSH facility in Pittsburgh focuses primarily on requirements and standards for mine and fire rescue helmets and corresponding breathing apparatuses.

The test stand used to test the mine and fire rescue hardware consists of an artificial lung that breathes through an attached head form for helmet interface. See Fig. 7 and Fig. 8. Metabolism of the test stand can be adjusted to reflect the respiration rates, humidity, and air temperature associated with human breathing characteristics at that set metabolic rate. The test stand can also be configured to measure the amount of CO₂ inspired with a helmet donned, which is the key feature the analysis needed to test the suit helmets. The inlet flow rate of air can be adjusted to within 0.1 cfm, flowing both clean ambient air as well as air injected with a supply of CO₂ to represent the maximum amount of CO₂ that the ECLSS suit loop can flow into the suit.

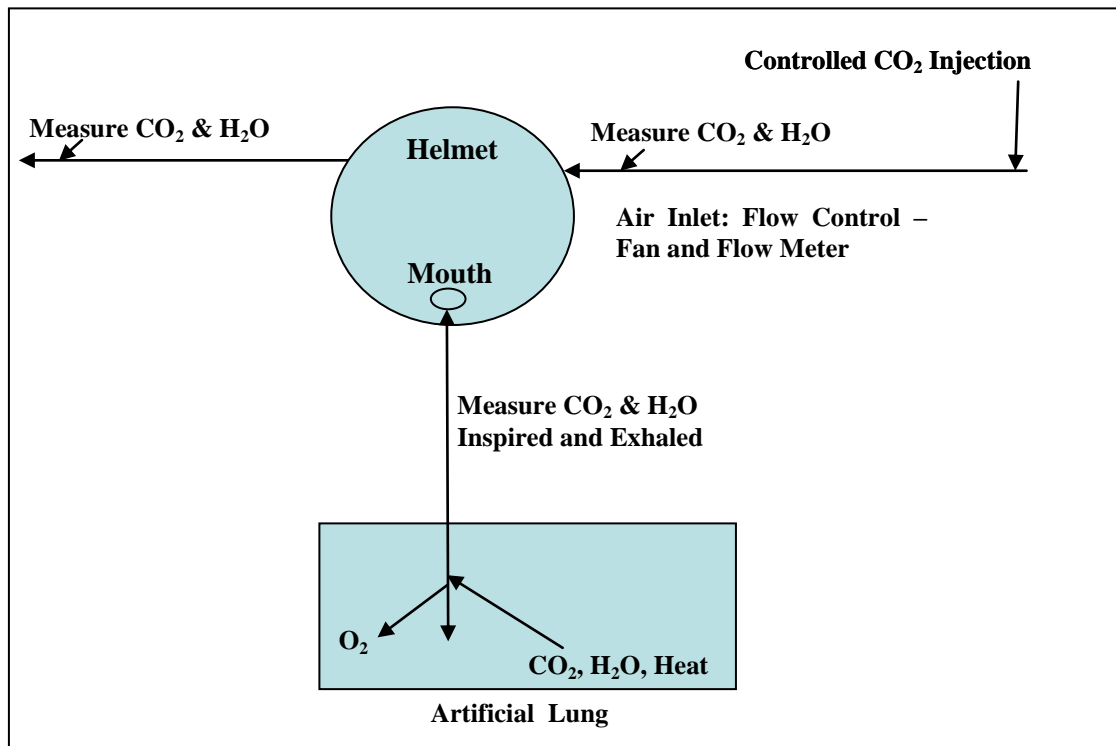


Figure 7. Schematic diagram of NIOSH test stand.



Figure 8. Actual NIOSH test stand.

Suit Helmet Test Articles

The analysis team used the Mark III hemispherical helmet bubble along with a neck wedge to build up both the conformal hemispherical helmet and the open configuration helmet. The Mark III open configuration helmet was placed on the head form with a piece of sheet metal curled at the ends in order to suspend the helmet above the head form to simulate the actual position of the helmet on a suited crewmember. See Fig. 9. A metal fitting was used as an interface between the air supply line and the neck wedge. The back part of the neck wedge acted as a duct to flow air from the supply line to the back of the helmet. Air then flowed up the back of the helmet, across the top of the helmet along the bubble, down in front of the face, and out of the helmet through the neck area.



Figure 9. Mark III open configuration helmets installed onto test stand.

The Mark III conformal helmet configuration modifies the open configuration helmet by incorporating foam barriers to simulate the facial volume isolation that occurs with helmet occupant protection inserts. This configuration used a horseshoe-shaped foam insert to isolate the volume of air in front of the face, as well as an additional air duct to flow air from the back of the neck wedge, through the foam insert. See Fig. 10. The air flowed to the top of the helmet field-of-view, along the helmet bubble in front of the face, and out of the helmet through the

front part of the neck area. A foam chin-piece insert was used to restrict air flow out of the helmet during some of the test runs; other runs were conducted without an insert. See Fig. 11.



Figure 10. Mark III Conformal helmet installed onto test stand.



Conformal with Chin

Conformal Without Chin Piece

Figure 11. Mark III Conformal helmet with and without foam chin insert.

The U.S. Air Force S1034 helmet is virtually identical to the model used for the CFD analysis. See Fig. 12. The analysis team actually modified the helmet from its original demand breathing configuration. The demand regulator at the back of the helmet was removed to enable the helmet to function as a continuous flow helmet, similar to the other helmet configurations.



Figure 12: U.S. Air Force S1034 helmet installed on test stand.

Mark III Open Configuration Helmet Testing

Testing of the open configuration helmet showed CO₂ washout performance characteristics that the analysis team did not predict. Since this helmet by design does not conform to the head form, the positioning of the helmet was often inconsistent, which led to noticeable variations in CO₂ washout results. Additionally, the CO₂ washout performance of the low-metabolic rate cases actually worsened when the air flow increased from 4.5 to 6.0 cfm. Although this helmet performed fairly well overall at 4.5 cfm, the real value of these test cases is an increased understanding of the performance characteristics.

During the first set of tests with clean air flowing (i.e. ambient air not contaminated with CO₂), the helmet performed well and with predictable results. CO₂ was injected into the air flow in the second set of tests. The improved performance results were not consistent with the team's expectations. See Fig. 13 and Fig. 14. This led the analysis team to believe there may be problems with either the instrumentation or the helmet placement. After a recalibration ruled out instrumentation as the problem, the team looked at CO₂ washout performance with the helmet positioned in different ways.

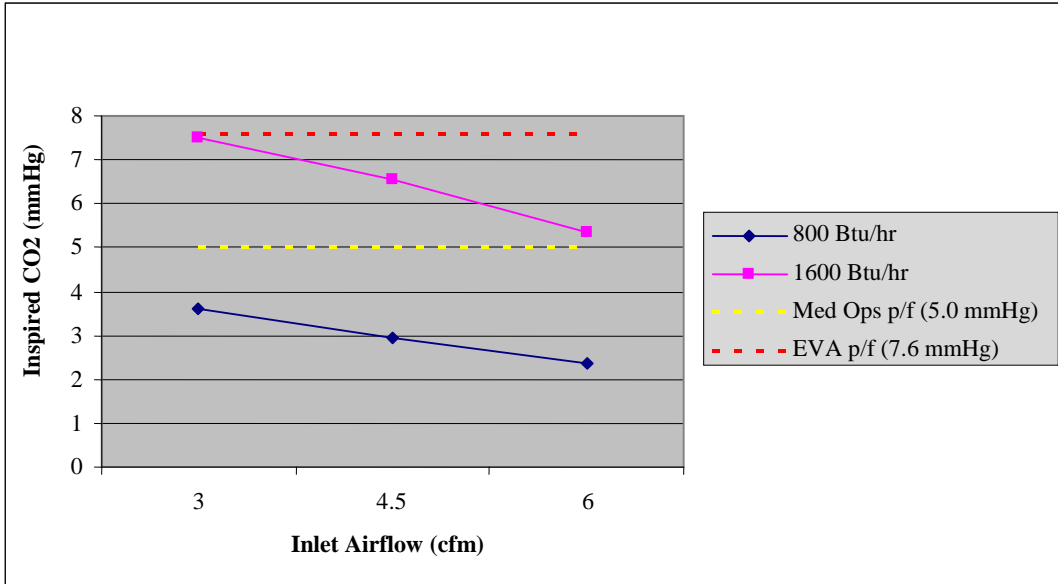
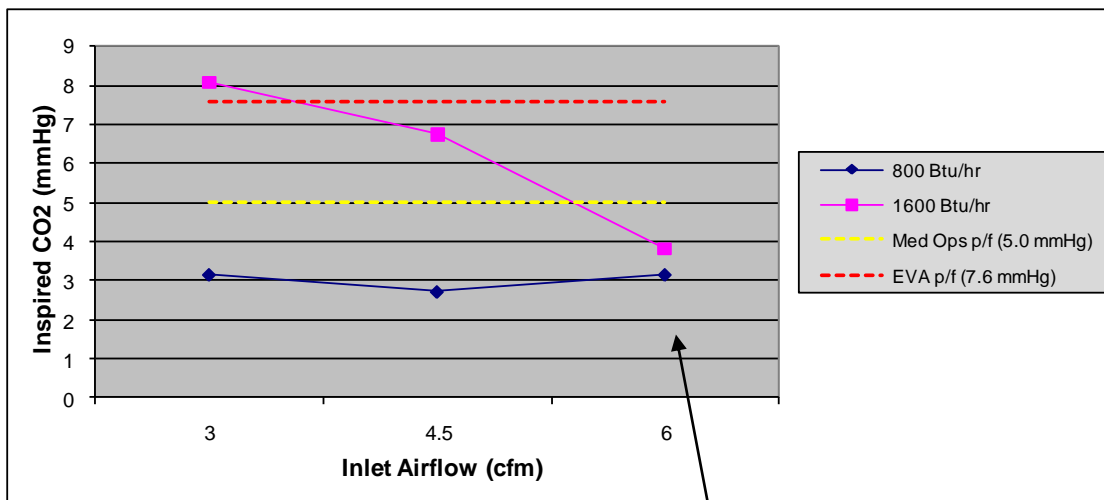


Figure 13. Day 1 - Mark III open helmet, no injected CO₂.



Note that inspired CO₂ increased as air flow increased.

Figure 14. Day 1 - Mark III open helmet, 2.3 mmHg injected CO₂.

Rotating the helmet about 30 degrees to the left or right of the head form along the plane of the neck made the most significant impact in CO₂ washout performance. By rotating the helmet, the flow of air was no longer in front of the face. Rather, it offset the flow pattern causing the air to flow along the side of the face, away from the breathing area. Inspired CO₂ increased by as much as 7.3 mmHg when running a 3.0 cfm clean air case at 800 Btu/hr. Canting the helmet forward also increased the inspired CO₂ by as much as 2.3 mmHg. The helmet was also canted to the left and right of the head form, resulting in slight increases in inspired CO₂. See Fig. 15.



Before: Neutral Position

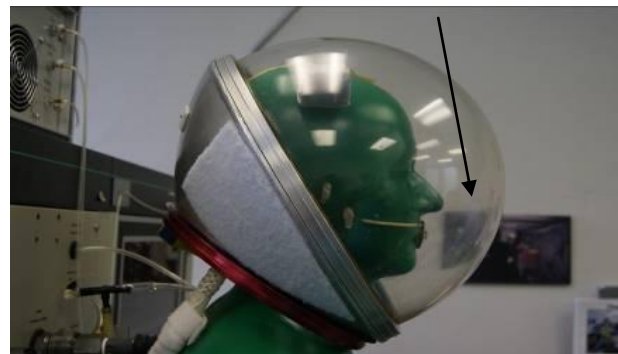


After: Helmet Rotated 30 Degrees

Note increased volume in front of face.



Before: Neutral Position

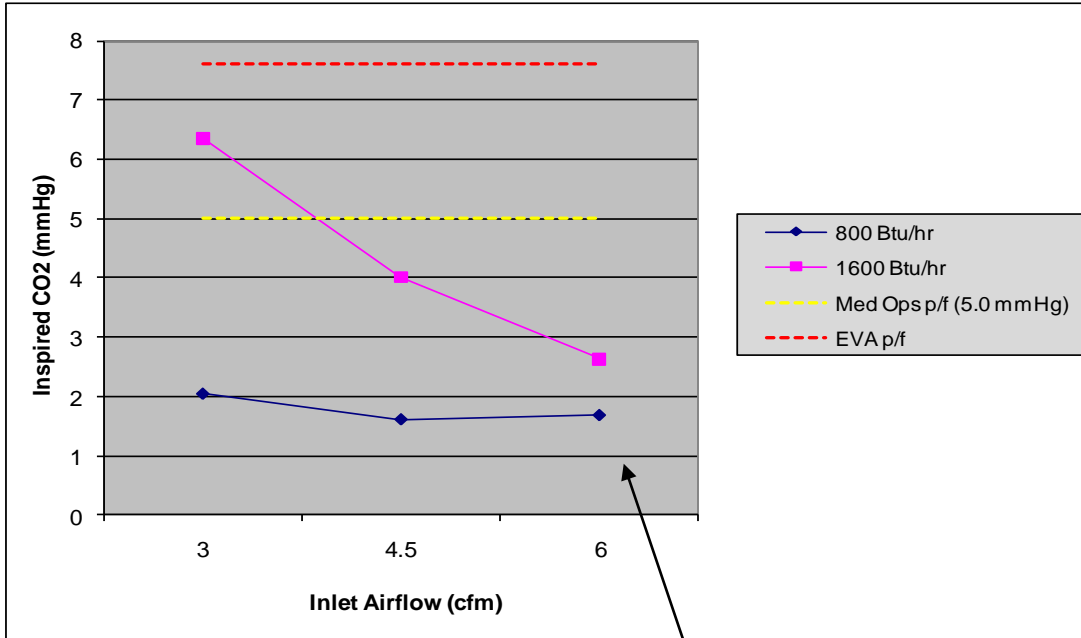


After: Helmet Canted Forward

Note the restricted air flow around front of neck ring.

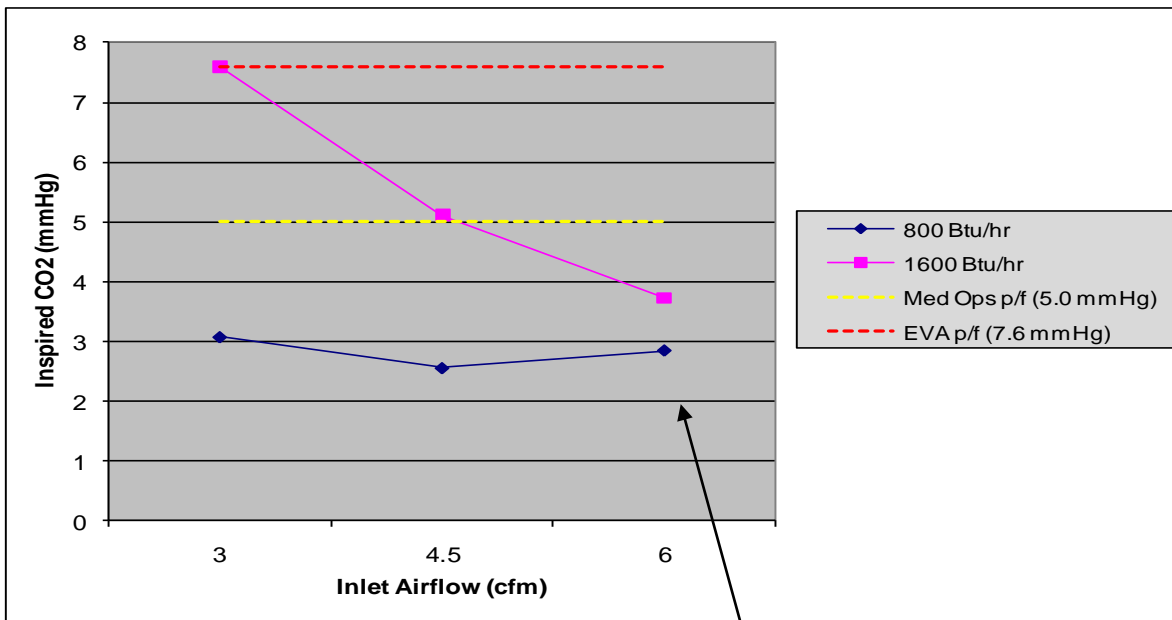
Figure 15. Mark III open helmet positions evaluated during troubleshooting.

The cases run with the repositioned helmet showed a high-level of sensitivity to the helmet placement onto the head form. Since the analysis team was not able to get a consistent placement, the data was not believed to be highly accurate. However, the trends of the cases that were run before and after the troubleshooting effort were useful in showing that the high-metabolic cases improved the CO₂ washout as the air flow increased. Conversely, the low-metabolic cases did not necessarily improve as the air flow increased. See Fig. 16 and Fig. 17. The latter scenario could not be explained during the course of this analysis. When asked by EVA if 6.0 cfm would be required or would it be optimal for CO₂ washout, these scenarios showed that more air flow is not necessarily better.



Note that inspired CO₂ increased as air flow increased.

Figure 16. Day 2 - Mark III open helmet, no injected CO₂.



Note that inspired CO₂ increased as air flow increased.

Figure 17. Day 2 - Mark III open helmet, 2.3 mmHg CO₂ injected.

United States Air Force S1034 Helmet

The analysis team expected the U.S. Air Force S1034 helmet to perform the best out of all configurations because it has proven itself in regular Air Force operations and because it performed well during the CFD analysis. However, although the S1034 performance was acceptable, it was not impressive. At 4.5 acfm with clean air flowing in, the partial pressure of inspired CO₂ at the high-metabolic rate was just under the 7.6 mmHg EVA success criterion. For the low-metabolic case, the inspired CO₂ was well under the 5.0 mmHg success criterion required by the space medicine group. The team was unable to perform test cases with CO₂ injected into the helmet inlet line due to schedule constraints. However, the team expected the helmet performance to degrade and fail based on the success criteria. See Fig. 18.

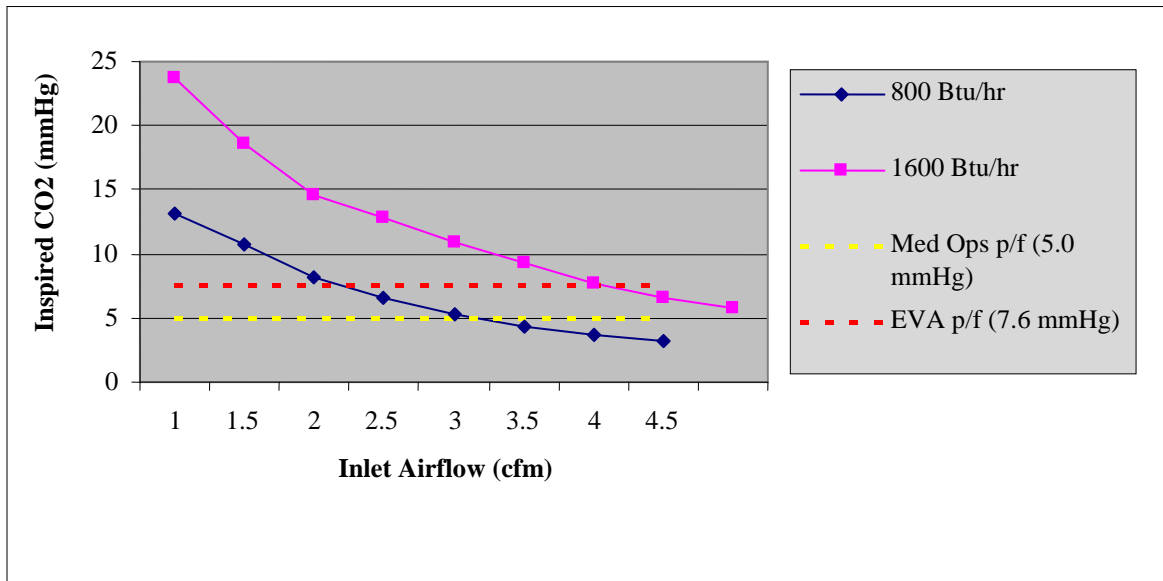


Figure 18. U.S. Air Force helmet, no inlet CO₂.

Because this helmet is a conformal helmet, the positioning of the helmet was consistent throughout all test runs. The helmet required a high-pressure inlet line from the air source that created enough pressure within the helmet breathing volume to make the helmet move up and down as the head form exhaled and inhaled. The amount of movement increased as the air flow increased, so testing ceased at 5.0 cfm to minimize the risk of damaging any hardware.

The S1034 helmet normally functions as a demand breathing helmet by design, which is different from the modified continuous flow test configuration of the S1034 used at NIOSH. The analysis team modified the helmet by removing the demand breathing mechanisms, but other inherent design features kept the S1034 from functioning as a true, continuous flow helmet. This potential function impendence needs to be investigated further in order to correlate this test data with the CFD data points for the S1034 helmet.

Mark III Conformal Helmet

This low-volume helmet concept performed about as well at NIOSH as the CFD model, which is to say that it did not perform particularly well. Most of the high-metabolic rate cases failed the EVA success criteria, with the exception of the 6.0 cfm, test point where no CO₂ was injected. This case measured an inspired partial pressure of just under 7.6 mmHg of CO₂. The low-metabolic rate cases performed better, yet all data points exceeded the Space Medicine success criteria of 5.0 mmHg. CO₂ washout performance did not change much when the chin piece was removed from the helmet. See Fig. 19 and Fig. 20.

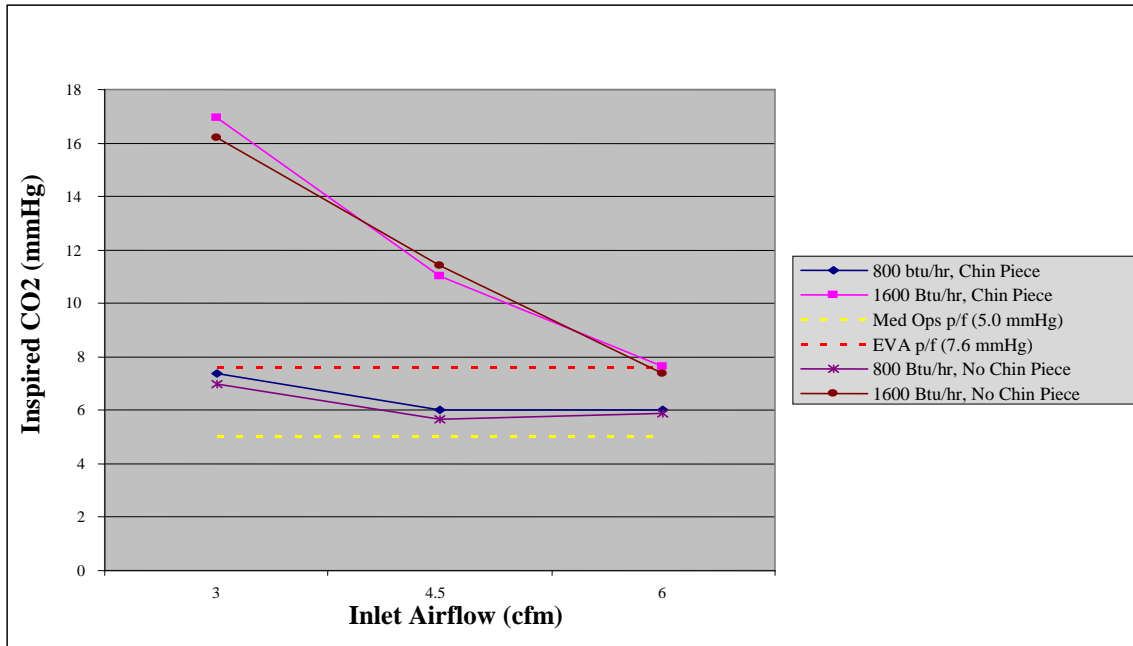


Figure 19. Results of Mark III conformal helmet, no injected CO₂.

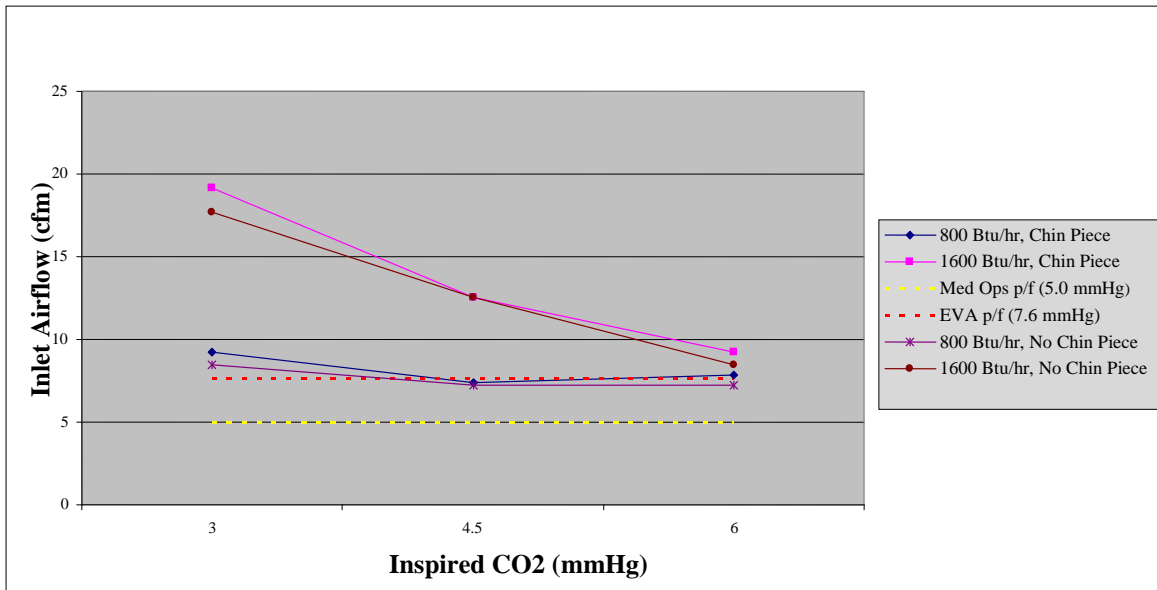


Figure 20. Results of Mark III conformal helmet, 2.3 mmHg CO₂ injected.

Alternative Configurations

After completing the scheduled tests, the team tested variations of the configurations previously detailed to characterize CO₂ washout performance with different helmet features. One set of runs used the open configuration helmet with the new air duct added to the helmet. See Fig. 21. Another configuration used the air duct and a neck dam made of foam with a cutout just below the chin to permit air flow. See Fig. 22. The last configuration used only the new neck dam and air flowed from the neck wedge in a manner similar to the open configuration helmet. See Fig. 23.

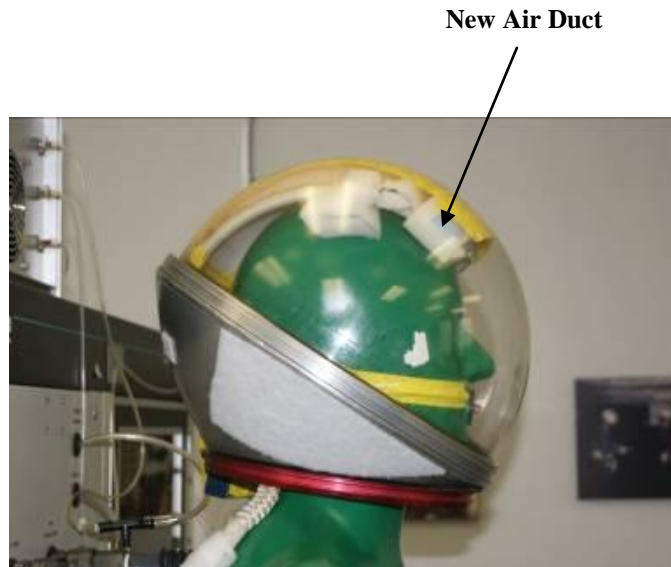


Figure 21. Mark III open helmet with new air duct.



Figure 22. Mark III open helmet with new air duct and neck dam.



Figure 23. Mark III open with neck dam only.

Of the three alternate configurations, the helmet with the air duct and neck dam performed best. It met both success criteria at 4.5 acfm during the low-metabolic rate runs, the high-metabolic rate with clean air, and the high-metabolic rate with CO₂ injected into the air supply. See Fig. 24. A possible rationale for the superior performance is that this configuration flowed air as a continuous channel into the helmet, across the oral-nasal region, and out to the environment. Based on the CFD models, the other helmets tended to mix fresh air with expired CO₂ instead of efficiently washing it out of the helmet. Tests run with a fire rescue Gentex[®] helmet during a prior trip to the NIOSH may support this rationale. See Fig. 25.

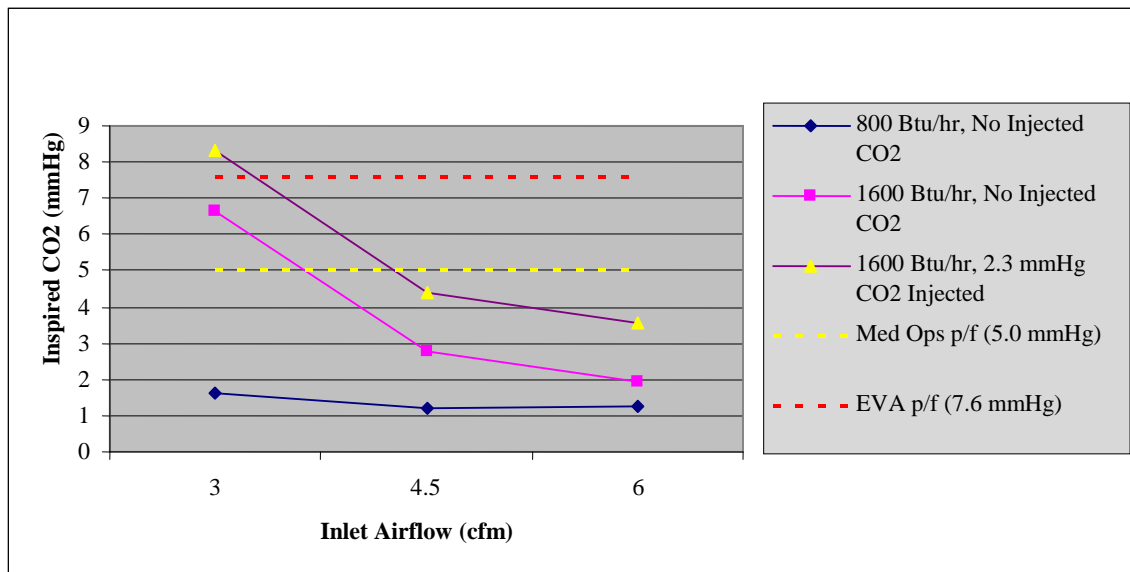


Figure 24. Mark III open helmet, neck dam, new air duct test results.

Gentex[®]
 Helmet and
 Head Form
 Installed
 onto Test
 Stand



Figure 25. Gentex[®] test configuration.

The Gentex[®] helmet test runs yielded unexpectedly favorable results at 3.0 cfm and 1600 Btu/hr. Using an oral-nasal mask that allows air to blow side-to-side across the oral-nasal region, it successfully washed out CO₂ to an inspired partial pressure of around 5.8 mmHg, well within the EVA success criteria. The common element between the Gentex[®] and the new air duct/neck dam configuration appears to be the channeled flow concept, whether it was top-to-bottom or side-to-side. The hemispherical helmet with occupant protection inserts also used a channeled flow concept, but the smaller volume may have allowed for more mixing and less washout. From a helmet development standpoint, this channeled-flow concept deserves further investigation as part of a design solution to improve CO₂ washout.

The other alternate configurations – air duct only and neck dam only – also performed well, with all results remaining under the EVA success criteria of 7.6 mmHg. Both configurations used the channeled air flow idea to a lesser extent than the duct/dam configuration. Enough channeling flow may have minimized the mixing of fresh air with CO₂ to provide improved CO₂ washout. See Fig. 26 and Fig. 27.

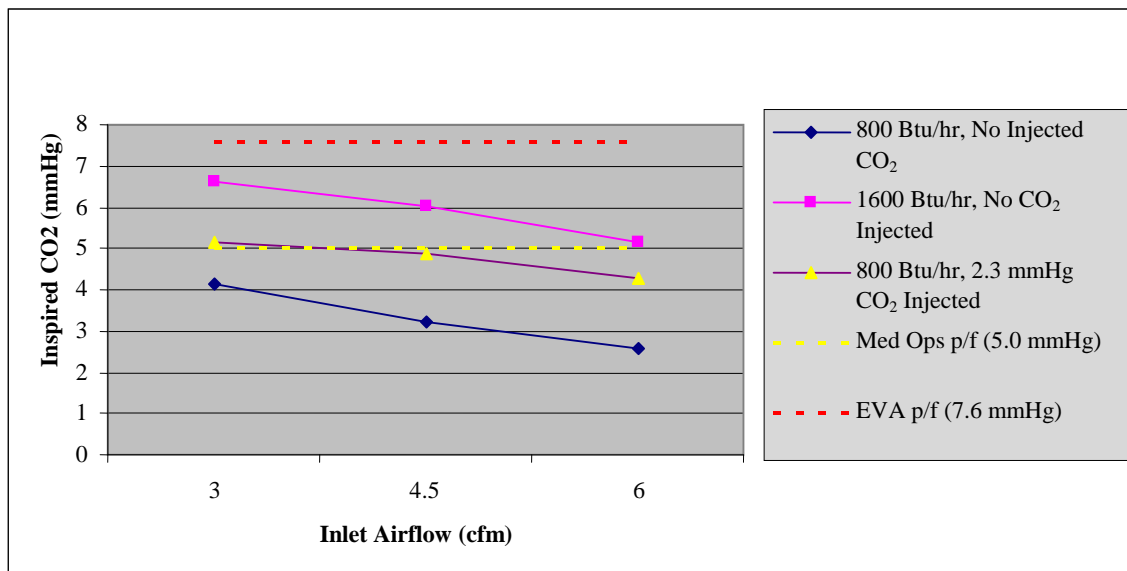


Figure 1: Mark III open helmet, neck dam.

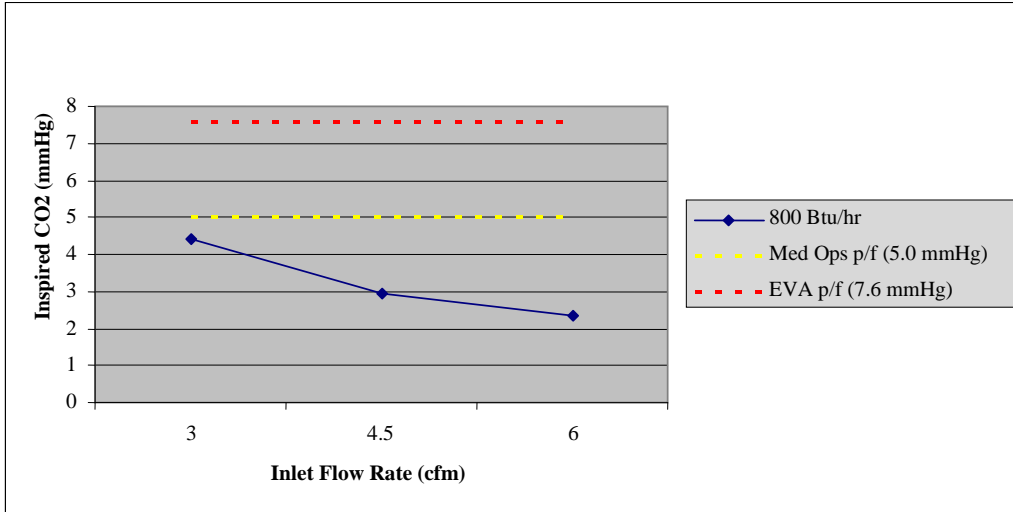


Figure 2: Mark III open helmet, new air duct.

V. Conclusion

The CO₂ washout analysis provided several data points that characterize CO₂ washout within space suit helmets. Both the testing at NIOSH and the CFD modeling showed washout performance trends that were generally consistent with each other. Some helmet configurations performed better than others, and it was clear that proper detailed design of the helmet is crucial to achieve proper washout. Several cases successfully washed out CO₂ at 4.5 acfm and this gave the analysis team enough confidence to recommend this air flow value. However, the definition of a success criterion for proper washout could not be agreed upon during the analysis. Given this disparity, the analysis team did not have a compelling rationale to accept air flow of less than 4.5 acfm. Additionally, the low-metabolic cases that experienced diminished CO₂ washout performance when the air flow increased from 4.5 to 6.0 acfm could not be explained. Thus, the analysis team recommends accepting 4.5 acfm of air flow from the suit loop.

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⁴Gilbert, John and Schentrup Susan, “Determination of Residual Carbon Dioxide During Forced Ventilation of a Hemispherical Space Suit Helmet - Final Test Report,” 31 January 1991.