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Pilot Breathing Assessment

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This appendix documents a dataset acquired from ground-tests of two F-35 jets that was analyzed using the tools developed in Pilot Breathing Assessment (PBA) for 105 scripted flights of F-15 and F/A-18. These tests were deliberately run as ground-test only to allow researchers to evaluate the F-35 breathing systems without confounding from aircraft parameters such as altitude, velocity, G-force, cabin pressure and orientation. Although these findings cannot be considered generalizable to all F-35 aircraft, they are sufficiently compelling to indicate the need for further investigation.

Acknowledgements

The PBA team would like to express gratitude and appreciation to the pilots who participated in this work. Your stories are the impetus for this document and your statements are the backbone. We hope this work represents your concerns and insights fairly and justly. We hope this effort will elevate the issues faced by the men and women of the F-35 community who stand ready to defend us.

1.0 Introduction

F-35 pilots interviewed by the NASA Engineering and Safety Center (NESC) Pilot Breathing Assessment (PBA) team have stated that perturbations in F-35 breathing systems can present a hazard to operations. Some pilots who have suffered Physiological Episodes (PEs) in the F-35 fault the breathing system for acute and chronic health conditions that have caused impairment for days, weeks, months, or longer. Pilot interactions with the F-35 breathing system have resulted in symptoms ranging from confusion, distraction, extreme discomfort and persistent fatigue, as well as lung inflammation resulting in permanent dysfunction. The breathing system may have contributed to ending the career (medical disqualification) of at least one interviewed pilot. Pilots regularly label certain aircraft as having consistently more difficult breathing systems than others; this appendix explores potential technical issues that contribute to these designations.

Pilot interviews prompted the PBA team to explore the behavior/response of the F-35 breathing system using the same empirical measurements as for the main study of F-15 and F-18 aircraft equipped with liquid oxygen (LOX) systems. PBA data from ground tests of F-35 Tail Numbers 11-5021 and 12-5042 documented perturbations of within-breath and between-breath flow and pressure response from the system. The comparisons show significant differences between the two F-35s as well as between the F-35s and the legacy aircraft in terms of breathing dynamics; these are of concern as there are potentially severe adverse system interactions between the pilot and the F-35 breathing system. Furthermore, comparisons between the two F-35 aircraft show differences in breathing dynamics supportive of the subjective labels of certain F-35 aircraft as “bad breathers”.

Both F-35’s tested delivered unpredictable flow at the beginning, middle, and end of the breath (intra-breath) that changes from breath-to-breath (inter-breath). Such rapid changes in the breath-to-breath supply forces the pilot to continually compensate by adjusting breathing rate, volume, and exhale/inhale force. When breathing requires conscious adjustments, rather than autonomous response, it distracts from the mission. Furthermore, this pilot-jet disharmony could create stress on the pilot, and result in discomfort, fatigue, and may ultimately lead to short-term and long-term physiological damage.

The F-35 data reviewed in this report were obtained from ground tests of two aircraft, one qualitatively judged as a ‘bad breather’ compared to the other, however, both jets were considered operational and fit for flight. The data measurements consisted of inhalation breath pressure, temperature, and flow. Although the ‘bad breather’ jet was found quantitatively worse with respect to tidal volume and asynchronous timing, neither was considered good compared to the legacy aircraft examined by PBA. Indeed, these data show that both jets exhibited asynchrony in flow and pressure that were quantifiably worse than any of those observed in the PBA test flights of F-15 and F-18 aircraft. These data, combined with several pilot observations, suggest the problem may be systemic to the F-35 breathing system design and not specific to a single jet.

In addition to the asynchronous pressure/flow behavior, the F-35 data from both jets showed wide swings (20 to 40%) in the concentration of oxygen (O_2) supplied to the pilot. The negatively synergistic combination of constantly changing pressure, breathing sequence, and inconsistent O_2 delivery increase the likelihood of adverse impacts on pilot physiology. PBA was able to specifically identify Breathing System Disruptions (BSD), or breathing sequence disruptions (BSDs), which have been observed in other aircraft, but are of particular concern in the F-35. Continuous breathing disharmony (disrupted inhale/exhale) and pressure/flow asynchrony can result in pulmonary micro-trauma (small tears and inflammation) of the alveoli, airway damage, and chest wall remodeling. High and/or variable O_2 concentrations may additionally contribute to cognitive deficits and cumulative trauma resulting in longer-term damage.

The human can adapt to abnormal breathing conditions to an extent, but continuous exposure can inevitably lead to lung injury. At the microscopic level, cumulative pulmonary ‘micro-trauma’ results in collapse and loss of function of the alveoli. On the macroscopic level, the body attempts to adapt through changes in respiratory volumes and rates, but the machine imposes restrictions that limit and eventually exceed the capacity of the body to adapt. Combined with high and variable O_2 concentrations, all available evidence suggests that cognitive insults and cumulative trauma can result in permanent damage.

In summary, rather than the breathing system responding to a pilot’s physiological needs, the pilot is forced to adapt to an unpredictable supply system with potentially adverse consequences. One may ask why such events are allowed to continue. Why do the pilots put up with it? In 2012, the NESC conducted an assessment of the F-22 pilot breathing problems. It was observed that:

> *The F-22 pilot community has come to accept a number of physiological phenomena as a “normal” part of flying the Raptor. These include the “Raptor cough,” excessive fatigue, headaches, difficulty breathing, and delayed ear blockages. The acceptance of these phenomena as “normal” could be seen as “normalization of deviance.”*

This normalization of deviance is part of the F-35 culture as well. Pilots interviewed for this report indicate the F-35 community will endure much adversity to be one of the elite that fly the nation’s newest fighter. Pilot interviews also highlighted an organizational concern to protect the F-35 program, specifying undue pressure to suppress information and ascribe breathing problems to pilots rather than the aircraft. Previously we have emphasized that PEs happen to pilots, not to planes. The end goal is a breathing system which supports pilot breathing requirements, not aircraft-centric provisions. Hence, measuring pilot breathing metrics is the foundational part of understanding this complex problem.

In contrast to the main PBA effort for F-15 and F-18, this small exploratory study was not intended to provide statistical significance for all F-35 aircraft. However, the results are sufficiently compelling to prompt further testing using the full suite of PBA sensors and analytical techniques to further identify and mitigate adverse breathing system behavior in the F-35.

1.1 Rationale for In-flight Pilot Breathing Data Acquisition

When the PBA began in May 2018, aside from the 1987 AGARD study on 3rd generation aircraft, very little was known about how a pilot breathes in the cockpit of an advanced modern fighter (Harding, 1987). No comparable in-flight physiological data had been collected even 5 years after the seminal 2013 article lamenting the "tremendous disconnect between what is known about the function of the aircraft and the function of the pilot" (West, 2013). After gathering both pilot inhalation and exhalation data from over 100 flights at NASA's Armstrong Flight Research Center (AFRC), the PBA was able to understand and characterize pilot breathing to a degree that was never available before. The analysis led to new ways of viewing those conditions that are detrimental to the pilot. Indeed, metrics have been established which now clearly indicate less than favorable conditions for the pilot and importantly, problems in the breathing systems as a whole. The PBA team reviewed, discussed, and even argued about these results before ultimately coming to a common consensus concerning the methodology and metrics used to measure pilot breathing. It was this team, trained, experienced, and ready that was offered the chance to review the F-35 data presented in this report. The F-35 data set is not statistically significant, but it was thoughtfully acquired, and it was more than enough to give this team of pilot breathing experts the evidence to make a number of judgements that will be found in this report. Additionally, comments obtained from F-35 pilot interviews are included to underline the points being made from the data.

The PBA interviewed five F-35 pilots from that small community. These pilots experienced adverse physiological symptoms while flying an F-35, including reported Physiological Episodes (PE). Detailed questions put together by NASA Human Factor experts were used to obtain the detailed information about these experiences with the F-35 and the individual PEs.

Some within the F-35 community may disregard the results presented in this report due to limited data; that would be a mistake. The importance of listening to what pilots are reporting about breathing dynamics cannot be overstated. This report provides detailed, data driven insight to help understand subjective pilot concerns about breathing and general stress in the cockpit. The NASA NESC team found instances of alarming problems in the F-35 breathing systems that should be corrected. It is our hope that this hard-earned knowledge can help our warfighters and better enable those responsible for the systems that keep them safe.

2.0 Introduction

Since the early 2000s, reports of breathing difficulty, adverse cognitive effects, and unusual symptoms have increased significantly in fighter and trainer aircraft, the so-called unexplained "Physiological Episodes", also known as PEs. The NESC performed an assessment of breathing problems in the F-22 in 2012. Later, they performed an in-depth study of the occurrence of PEs in the F-18, which was published in 2017. The Pilot Breathing Assessment (PBA) flight test program is a follow-on to the F-18 study using NASA aircraft to gather baseline data on pilot breathing. Surprisingly, such baseline data did not exist for advanced fighters, possibly because the tools for airborne collection of breathing data have only recently matured to the point of enabling collection in the flight environment.

PBA completed 115 documented sortie flights, using six NASA aircraft: four F/A-18s and two F-15s. Data collected in the PBA study includes sensors to monitor pressure, temperature, flow, and gas concentration during inhalation and exhalation, instrumentation dedicated to jet performance (altitude, speed, etc.), and qualitative observations of the pilot. The description, data, and analysis of these flights are published in the NESC Pilot Breathing Assessment (NESC-RP-18-01320). Ultimately, the analysis of this breathing data has led to significant findings, observations, and NESC recommendations which have advanced our understanding of in-flight "breathing dynamics" referring to the breathing system performance and the interactions between the aircraft breathing system, the flight environment, and the human pilot.

In June 2019, the NESC PBA commenced a further dedicated investigation on the breathing dynamics in the F-35 aircraft, facilitated with data and information provided by US Air Force Physiological Episodes Action Team (USAF PEAT). The goal of this effort was to examine the unique pilot/jet interactions in the F-35 using the tools, techniques and insights amassed during the PBA test program, particularly the insights gathered during the investigation of MBU-20/P mask malfunctions. Thanks to the PEAT and additional data gathered directly by the NESC, the PBA analysis of the F-35 uncovered new and compelling evidence that F-35 aircrew are exposed to continuous chaotic and disharmonious breathing system dynamics that have the potential to cause physiological insults significantly detrimental to both short-term and long-term pilot performance and health.

The conclusions drawn from these data are new, unique, and compelling with respect to the F-35, drawn from insights gathered as a result of the detailed analysis of pilot breathing during the PBA program. This is not, however, a comprehensive analysis of the F-35 breathing system. The tests were limited to two short ground tests of two aircraft. These were deliberately designed to assess the breathing system performance without confounding from aircraft flight stressors from changes in altitude, cabin pressure, G-force, orientation, and velocity. Although limited, these data suggest systemic problems with the F-35 breathing system and life support equipment and call for a comprehensive investigation. This investigation should include sufficient aircraft to represent fleet characteristics and use appropriate instrumentation to ascertain pilot breathing dynamics during representative in-flight conditions. The analysis refined in PBA highlights compelling technical and medical concerns that should be cause for investigation and action.

2.1 Pilot Experiences

Pilots describe breathing in the F-35 as being significantly, perceptibly different from the breathing environment in legacy aircraft, such as the F-16. The flying and combat employment of an advanced fighter aircraft is cognitively challenging; breathing should not be a distraction.

However, no longer being able to breathe normally or think clearly takes immediate priority over any primary task operation. This distraction does not end with that single experience. Pilots report that previous negative breathing experiences induce pilots to regularly assess their breathing and engage in specific lung exercises while airborne as cautionary protections. The most powerful evidence of these breathing discrepancies comes from F-35 pilot reports.

The importance of listening to what pilots are reporting about breathing dynamics cannot be overstated. F-35 fighter pilots are a particularly elite community. They universally like the aircraft to the point of being protective advocates and appreciate the F-35 for its advanced tactical utility and survivability in combat. Fighter pilot psychology is severely disinclined to overreport or exaggerate minimal issues. Additionally, this is strongly disincentivized due to concerns about the program, as well as personal career. As such, when a pilot risks highlighting herself/himself to discuss an issue, or an emergency is declared, symptoms and physiologic effects have surpassed a very high threshold of significance.

The NESC team has gathered and analyzed reams of flight data, but the subject matter expertise of the pilot provided invaluable insight in guiding the interpretation of the relationships and dynamics observed during flight. The combination of pilot reports and physiological monitoring data is what enabled the findings in this report. The importance of thorough and well-designed interviews was emphasized in the NESC F-22 Report, the NESC Report: F/A-18 and E/A-18 Fleet PEs, and nearly all assessments and investigations conducted. That lesson is applicable in the F-35 as well.

During the course of their work, the Pilot Breathing Assessment (PBA) team was made aware of safety concerns within the F-35 pilot community. The PBA was informed that data had been collected with a testing device similar in build and version to what the PBA was using to examine a similar question in a different setting. Thus, the PBA was in a position to examine these data using analysis techniques developed to assess the PBA flight data.

The NESC team conducted a number of interviews during previous aircraft investigations. These interviews offered a holistic perspective of the person-task-equipment triad that exists within the physical-social-organizational-policy framework. In particular, the individuals who interacted most frequently with the system (pilots/maintainers/flight docs) offered the greatest insight regarding the variability of the PE problem and by collecting and aggregating these individual data points provided routes for further examination. This interview presence established trust within the pilot community.

2.2 Pilot Interview Results

PBA conducted five (5) interviews on-record and in an official capacity to capture a range of F-35 pilot perspectives concerning the breathing system, common symptoms, and individual examples of physiological episodes (PE). The goal of this section is to allow a better appreciation of the pilot concerns and to gain an understanding of the cost associated with continued lack of response.

Five F-35 pilot interviews were conducted by a team of three NESC PBA researchers: a flight surgeon, an F-35 SME, and a human factors SME. Each interviewee was provided a NASA Privacy Act Notice which indicated the protected status of the interview and all materials associated with the interview. All interviewees provided explicit consent to video/audio recording, interview transcription, and inclusion in this report. All data are reported in aggregate to maintain privacy.

Each interview began with the pilot account of events related to the flight that induced a reported or unreported PE with specific information about the in-flight event, post-flight procedures, and recovery. This was followed by a period of question and answers for clarification and expansion. Finally, pilots were asked to provide perceptions of overall concepts across all airframes such as breathing experience, previous symptoms, common symptomology, and current processes.

As supported by data in Section 5 of this report, the asynchronous breathing and pressures observed in the F-35 breathing system are a significant safety hazard to the pilot. This hazard exhibits as causal to acute and chronic health conditions that impact mission performance and impair the pilot.

Pilots report that interactions with the F-35 breathing system generate symptoms ranging from mild discomfort, cough, and fatigue, to confusion, distraction, extreme discomfort, and near incapacitation. Some symptoms resolved in a range of minutes, hours, or days; others are potentially permanent.

Multiple pilot statements indicate an adversarial relationship with the JPO and include statements that reflect a) a significant chilling towards pilot reporting, b) an organizational bias to indicate non-aircraft related causes, and c) an organizational bias to attribute causation to the pilot such as psychogenic/psychosomatic origins, poor motivation, insufficient training, or inappropriate biological preparation habits. Pilot statements indicating concerns regarding the safety and adequacy of the system were provided to the JPO in verbal and written form, as well as in the formal PE reporting process.

2.2.1 Pilot Perceptions

A physiologic episode (PE) as defined by the U.S. Navy is when a pilot experiences a loss in performance related to insufficient O_2, depressurization, or other factors during flight. A simplified description of human perception provides a basic framework related to pilot subjective reporting. The senses provide raw sensation information that requires organization and interpretation. Perception is where the conscious experience of sensation is formed, influenced by factors such as present context, training, past experience, principles, and cognitive heuristics/biases. Ultimately, a pilot experiences sensation information and interprets the meaning.

The complex process of perception is hindered during suboptimal conditions or hazardous states of awareness such as hypoxia. The brain goes to extreme lengths to accommodate, but hypoxia dulls sensations and obfuscates perception. Onset is typically very slow and flying duties alone may distract the pilot enough to delay detection until the hypoxia is advanced. Hypoxia is particularly dangerous because the subjective experience of common symptoms can be confusing. For example, headache and nausea are uncomfortable, fatigue can induce poor decisions, and euphoria is either pleasant or induces a false sense of calm.

Due to the danger, pilots undergo frequent hypoxia recognition training to learn their individual signs and symptoms so as to recognize when intervention may be required. There is a distinction between hypoxia signs and symptoms (FAA, 2008). Signs are detectable by others, but are more difficult to detect by the hypoxic person. Typical signs of hypoxia include rapid breathing (tachypnea), cyanosis, lethargy, poor coordination, and poor judgment. Symptoms are sensations the person can perceive and use to assess their hypoxic state. Hypoxia symptoms are individual to the person in terms of appearance and intensity and remain individually consistent over time. Typical symptoms of hypoxia include air hunger, fatigue, nausea, headache, dizziness, hot & cold flashes, tingling, visual impairment, and euphoria.

The F-35 pilot population is small. In general, the vast majority of PEs and symptoms are unreported since they do not meet the pilot's threshold to declare an emergency. Thus, out of the approximately 40 documented/JPO investigated PEs, the five pilots herein may be identifiable simply by revealing particular details of their PEs or interactions within the reporting structure as known within the pilot community. Some of these pilots required greater privacy protection, so a more restrictive approach was utilized when reporting their incidentals. Some pilots permitted more extensive reporting, including summary statements regarding the F-35 and interactions with the JPO. Brackets within quotations indicate areas where additional content was provided for context, or where sensitive details were omitted.

Concerns regarding the F-35 breathing system were raised by pilot reports in 2012, during pre-production testing and have continued throughout the program development through to current-day mission flights. The early pilot reports were neither vague nor insignificant and included the following statements:

- "It was trying to kill me"
- "The system was working as designed, but didn't actually protect me"
- "Maybe we had some fundamental misunderstandings of what the design of the system needed to be and we didn't have as much physiological understanding of the human/machine system as we needed."

A pilot noted that, at the time his concerns about the breathing system were raised, there were other on-going investigations specifically related to potential breathing gas contamination concerns. He stated that his concerns were met with program leadership opposition in the form of explicit and implicit rejection and suppression:

- "There was tremendous amount of concern amongst the [F-35] enterprise that the program was vulnerable, at the time, and so there was a lot of pressure to continue testing, continue pressing forward. The team as a whole, and especially the program office folks who were in charge of the life-support system at the time, were fairly motivated to assign [my symptoms] to something that was not attributed to the jet. That was my perception that was what they were trying to do, find a way to have it not be the jet so they could press."
- "They were able to, again, sort of talk themselves into using those words and saying 'well, maybe it was hypercapnia, maybe it was hyperventilation, but in no case is it something we need to change the design.'"

One pilot reported this summary statement regarding the F-35:

- "It's the new normal. Breathing in this jet is different than sitting here talking to you and breathing. It shouldn't be, in my opinion, but it is. Talking against positive pressure is different than talking against no positive pressure. The schedule of the cockpit pressurization sometimes changes the pressure in the mask, I don't know if it should be doing that or not, sometimes it does do that. The pressure breathing for G is slightly, not slightly, it's different than what I had been previously accustomed to. And so, it is routine for me to notice now, put it like this: I NEVER thought about my breathing, EVER, in the Strike Eagle. Never. I never, it was not a conscious thought, I didn't ever, it was never brought forward into my conscious thinking about breathing it was just something I was doing and I never considered it. Now it is something that I am conscious of, routinely, in flight; I'm conscious of how I'm breathing, conscious of making sure I'm controlling my breath, taking a deep breath, to expand my lungs every 10/15 minutes or so, I make sure that I do that. That could be a factor of this thing happening to me or it could be a factor of just breathing in this jet is different. I think if you were to ask other pilots that they would, my opinion is, of course they have their own opinions, is that the breathing in this jet is different than breathing in the Viper, the F-15 C or E, the A-10, or any other platforms, F-22, that they've come from, even the hornet. We have guys here that have flown all of them. It's just the different apparatus, a different feeling. And so now every sortie I am somewhat conscious of how I'm breathing, and how I'm interacting physiologically with the jet."

Another pilot reported this summary statement regarding his experience in the F-35.

- "The overall experience was one of extreme, you know, it's difficult to convey to other pilots and other people how absolutely disconcerting it is to be cognitively bamboozled like that. Because you know there's something wrong with you, you can't convey it, and you don't know why, and you don't even know the why to the why. Don't even know where to begin. 'Hey, what's wrong with me?' 'I don't know,' well, that only makes it worse, right? Which, okay, potentially psychologically, is just concerning on all levels, even though intellectually you kind of know 'hey, I'll be okay. I'll just go to sleep and this will all…' But for somebody whose entire life you are relying on your brain to be able think, and to fly, and to not be able to connect those words causes a level of concern. The jet attacked me. That's the essence of the way I felt. Even though somebody else might go, 'Oh, you're just a little bit off, go sleep it off, shake it off, shake it off.' Right? This was an entirely different level going through that experience and if it were to have happened while I was still flying, that's the thing that's the most concerning. Right? Because now it calls into question your ability to handle an emergency. That's the interesting dichotomy, I think I could have flown and landed the aircraft if everything was fine, but now it's kind of like the insidious where… you know… you always hear about the people going to sleep in the car in the garage, right, it's kind of the apathetic, just comfortably go crash, right? That's the concern. I would just not be able to make a decision, not be able to think and connect it airborne. If that had happened, there's nothing I could do about it. There's no control over it. As a pilot, you like to be able to control and take what actions you can. Nothing I can do! Nothing I can do to prevent it, fix it, and potentially maybe it's causing long-term harm to my health. So, that's the thing to convey. Maybe it's difficult to convey how that felt. Well, that's it.

To be clear, all pilots identified the F-35 as an asset to the warfighter. Here are a few summary quotes for positivity and perspective:

- "The F-16 had some significant growing pains as it was introduced as far as there were medical factors, it was routinely killing pilots with GLOC and spatial disorientation, but that was several decades ago. With time, effort, investigation, a merging of aerospace and aeromedical efforts, these were overcome and went on to become one of the most successful fighters in history and I'm confident the F 35 will do the same."
- "The jet is still providing an environment that, although not optimal, I don't perceive as actually dangerous. These UPEs certainly merit further investigation, but they haven't killed anybody. I'm gambling my life on it, so I think that's one of the more significant endorsements I can provide.
- "No pilot experienced significant enough symptoms that they have to stop fighting and address that over the tactical problem." [specific to F-35 combat deployment during actual combat, cessation of simulated combat has been reported]
- "Overall, pilots trust the jet."

One pilot would never fully recover and would be medically disqualified from flight shortly after his first reported PE. This individual may be identifiable within the pilot community due to the number of individuals with such a description. With his permission, his experience was included in greater detail and in his own words via transcription, to provide the reader greater insight into the pilot's perspective during this event, his recovery, and the lasting impact. To encourage satisfactory document flow, only a small number of direct quotes from pilot interviews are provided to support these clusters; however, all relevant quotes have been de-identified and included in Appendix 7.1 for further reading.

2.2.2 Pilot Symptom and Perception Clusters

In human subject research, the interview is one type of qualitative research methodology frequently used to collect individual instances of subjective experience. Like in quantitative research, once the interview data are conducted, the responses are aggregated and analyzed for emergent properties that reveal common themes generalizable to the content area in question. This analysis method is well-supported in the literature, but does require advanced expertise in human subject data collection and the subject matter area to conduct with precision and accuracy while avoiding common commission or omission errors.

These interviews revealed several pilot symptom and perception clusters. Here, clusters are conceptual groupings that emerged after the identification of highly similar statements and the subsequent interpretation of shared characteristics. Adverse symptomatology was reported across wide spectrum of flight profiles and pilot demographics (e.g., flight hours, age, and expertise). These symptomatology does not appear to be specific to individual differences or task performance. Pilots reported adverse symptomatology across the spectrum of individual differences and characteristics. This range included nascent pilots with low-hour and no previous aircraft experience to elite pilots with instructor qualifications, multiple airframes qualifications, and many hours of previous experience including extensive combat experience. Pilots reported adverse symptomatology across the spectrum of flight regimes ranging from straight and level, administrative, non-demanding phases of flight, to flight that is physically and cognitively intense. Quotes for this cluster have been excluded as detailing individual-specific characteristics of demographic and flight profile would compromise the privacy of our pilots.

The remainder of this section will consist of a cluster title, a summary or description of this cluster, and relevant quotes to demonstrate sufficient support for the grouping.

Cluster 1: The F-35 breathing environment and physiological experience is dissimilar to a) other aircraft flown and b) normal physiologic breathing. The F-35 breathing system noticeably discourages normal breathing function via high-pressure, pressure surges, and hyperoxia.

Pilots reported the breathing mechanics specific to the F-35 as readily detectable and distracting. Pilots negatively compared the F-35 breathing environment to any previous aircraft experienced, and to the normal environment defined as that found external to the aircraft. The characterizations involve the increased exhalation pressure, the difficulty inhaling, inter/intra-breath pressure surges, and the latency in the cycling of the pressure. In particular, when considered in aggregate, the pilot statements suggest the hyperoxic environment and high exhalation pressure modulates in-aircraft breathing patterns to be distinctively different from normal ambient physiological environment. High exhalation pressure causes an inability to fully exhale without intentional and forceful exhalation. The hyperoxic environment perceptibly reduces the respiratory drive. A perceptible and pervasive aberration in breathing is a sensation of lung hyperinflation relative to normal respiration (due to increased Functional Residual Volume and/or due to increased mask exhalation pressure). Other perceptible differences are paroxysmal sudden intra breath pressure changes, difficulty exhaling completely, latency in gaseous supply from the aircraft, and reduced respiratory rate.

Quotes include:

- “The respiratory environment is not, still, is not optimized for normal human physiology”
- “F-35 is known to produce erratic oxygen output both in concentration and in pressure. Some latency in the pressure delivery, or a lag in the system, as far as the pressure delivery. It’s perceptible.”
- “What I do know is that breathing in the F-35 is different. Breathing in [Strike Eagle] off of an MSOGS was a different experience than it is breathing out of the F-35. The F-35 is different in the fact that it has positive pressure all the time, not just pressure breathing for G but positive pressure in the mask. It’s different in the fact that the ECS environmental control system in the F-35 sometimes surges, sometimes pulls back. It’s a different physical environment that you’re in and the breathing is different. The cockpit pressurization schedule above 25,000 feet is different, it feels different on your body. It’s like hard for me to describe quantitatively the difference, but it’s different enough that you feel different.”
- “You kind of have to begin the exhale as an event, and then once that all starts, and the flow begins, then kind of exhale normally. So, I guess another way to describe it, and this is not an accurate mechanical description, but the feeling was kind of that it was like a sticky valve, both directions. You, kind of, have to

pull to get the inbound air going and then once the valve is flowing that I could breathe in with big continuous motion. And the same thing, I had to initiate the exhale, so a sticky valve feeling in that sense, and then once the exhale began, I could just go ahead and exhale normally."

- "The positive pressure isn't really, in my thinking, isn't so positive. It can be annoying."
- "Sometimes the F-35 just provides a whole bunch of pressure into the mask for unknown reasons, I don't know why but it does, it makes exhalation difficult"
- "Sometimes even in a single exhalation there could be a change in the pressure. So there's like a kick back and it can actually bite off a radio call."
- "Occasionally, especially on startup, you'll get a sudden decrease in pressure, so it's actually like a sudden choking from the jet, - there will be a sudden decrease in flow, pressure that might last like 10 seconds or something like that but then it resolves. But it will get your attention."

Cluster 2: There is a distinct breathing system disparity across F-35 aircraft with no clear explanation or solution.

Pilots detect a very clear difference in the breathing system between aircraft. This differential is most related to the pressure cycling throughout the respiratory cycle. This difference was reported and met with no solution nor reinforcement to continue in reporting. Pilots report that detecting stark deviations has become normalized such that pilots commonly refer to aircraft as "easy breathers" and "bad breathers" which has led to early notice of hardware failure or non-annunciated failure.

Quotes include:

- "There is noticeable change between jets, and some are easy breathers versus more difficult breathers."
- "Difficulty breathing off the oxygen system which led to, kind of, a mild shortness of breath symptom that would come and go, based on how cooperative the breathing system was at the time."
- "It was just a hard-breathing day. And the thing that just stuck in my mind that it was just way harder than normal to breathe without any definitive smoking gun as to what was causing it. I [informed the program office and the head of the maintenance] said 'hey, I just want to give you a heads up, this just breathes strange and it was very hard and it just really caught my attention, but there's nothing… I can't say anything one way or the other for you guys to go fix… So I just wanted to kind of let you know, and just talk it over him you' and they're 'oh, alright, well, just let us know if you think of anything else.' So that was the end of that." The next day I flew an entirely different jet. Same mission, profile, same rough temperature, same place, pretty much everything the same except different jet. Another F-35A. Another Air Force variant. And flew and the breathing was just night and day. So, I went from probably the worst breathing jet that I've ever flown in my life in terms of, it just struck me, that 'hey this is really, really, really, difficult' to nice, easy, breathing, and the contrast between the two of them was just what really caused me to highlight it. So, I thought, 'alright, this is… this is something there. This is real.'"

Cluster 3: Symptoms are frequent and variable among pilots and tend to mimic pilot-specific hypoxia symptoms. However, there are additional individual symptoms that are F-35 specific and learned exclusively from flying the F-35 that suggest additional pathophysiology.

A PE report is not an exclusive indicator of symptomology among the pilot population. Pilots often indicate experiencing symptoms that are detectable, but not as significant as to require a change in the sortie, a knock it off, or early return to base. Pilots may report a significantly increased level of fatigue after sorties. This fatigue is reported as unlike any post-flight fatigue experienced in other aircraft. The fatigue is so severe, some pilots report being unable to conduct a normal day following some flights. This fatigue may even last several days.

Common symptoms that are formally reported and/or informally discussed with flight medicine personnel include pronounced/idiosyncratic post flight fatigue, post flight cough, mild nausea. Other significant symptoms observed include cognitive slowing, confusion, lightheadedness, and dizziness. Pilots report a significantly increased level of fatigue after sorties. This fatigue is reported as unlike any post-flight fatigue experienced in other aircraft. The fatigue is so severe, some pilots report being unable to conduct a normal day following some flights. This fatigue may even last several days.

Some symptoms are predictable and considered to be related to inflight maneuvers or environment (e.g., tingling in the distal extremities). Some pilots report consistently experiencing symptoms for high altitude flights – flights with portions at or above 38k - 40k feet above mean sea level (MSL). The symptoms are lightheaded and dizzy, consistent, do not reach severity to declare an emergency, and resolve upon descent below 40. As these symptoms are so predictable, these pilots will preemptively go on the backup O_2 system before going above 40k ft.

Other symptoms are secondary to aggressive changes in altitude (e.g., climb or descent). Some pilots report consistently experiencing symptoms in an aggressive max performance climb such as climbing from administrative airspace transition altitude, around 10k ft up to about 20k feet. This maneuver results in 1-2 minutes of numbness and tingling in the hands and fingers which these pilots expressed as similar to those experienced in the hypoxia chamber.

Many pilots report several hours of nonproductive dry cough after every sortie with no other symptoms. For some, the cough begins late in the sortie, persists for 3-4 hours after landing, and gradually resolves. Another cough symptom presentation begins with a sudden onset coughing fit following rapid tactical descents and onset of G such as: dropping from 20k MSL down to 5k MSL. The cough would become sudden with severe onset and then persist though landing and into postflight, nonproductive, dry cough for several hours in duration. Similar symptomology was previously reported in investigations of the F-22 “raptor cough”.

Prominent quotes:

- “Pilots experience symptoms in the jet, they notice, but they’re not at the threshold that they consider necessary to declare or that they’re willing to flag themselves, highlight themselves, over.”
- “There’s been a lot of questioning with these events as far as whether or not it is psychogenic but out in the aircraft, I felt no anxiety whatsoever”
- “I think somebody asked me if I was hyperventilating or something, which was ridiculous, I was not anxious, there was no increased respiratory rate.”
- “After about 10 seconds or so, I felt my hypoxia symptoms from the altitude chamber get to the point where they were now part of my consciousness. So, in hindsight, I would’ve probably said that they had been gradually coming on, but it became part of my consciousness at that point.”

- “Lightheadedness and the blurred vision”
- “I was experiencing nausea, call it low-grade. It’s actually something I get in the jet fairly routinely.”
- “At one point I noticed [the numbness in my extremities] all the way up to the top of my calf towards my knee on both of my legs. I had only been in the flight for 10 minutes when that onset began. And that’s not a normal symptom.
- “I didn’t feel like there wasn’t physical air being brought into my body, I felt like in the ROBD, I’m breathing but I’m not getting that satisfaction of breathing, I’m not being fulfilled, my breathing isn’t doing anything. That’s why wanted more. I was air hungry.”
- “I couldn’t fully inflate my lungs [For several hours post-flight]. I’d get that pressure and burning sensation in my lungs, trying to expand my lungs”
- “It’s worth noting, after landing, I felt, again, pretty out-of-it, fatigued, and even a little bit confused.”
- “I was inappropriately confused at that point. Nothing manifested in the air, but I could definitely detect a cognitive slowing and confusion on the ground, after landing.”
- “I’m looking at the switch and I can’t remember which direction, which is telling that I’m not cognitively with it, I can’t remember which direction to turn the switch. I’m looking at it. I don’t know which way to turn it.”
- “You’re still dragging for a solid two days afterwards.”
- “I tend to experience more post-flight fatigue in the F35 than I have in previous jets. That’s actually really common, among F 35 pilots, previously experienced. Definite postflight fatigue.”

Cluster 4: Hypoxia recognition training as it currently exists is not a sufficient match with the respiratory environment in the F-35 when compared to the symptom exhibition and mitigation needs experienced during actual flight.

Some pilots reported inconsistencies in the symptomology between hypoxia awareness training and the actual onset of physiological symptoms in the aircraft. Pilots reported this expectation/reality mismatch caused a delay in enaction of appropriate response. Pilots suggested that increased ROBD training would be insufficient as that only induces simple hypoxia which does not capture the complexity of symptom exhibition. Furthermore, ROBD training was reported as counterproductive as symptoms in training were resolved in seconds while in several observations, symptoms remained much longer. This kind of training conditions the pilot to anticipate an immediate resolution of symptoms when engaging the BOS which is inaccurate.

Quotes include:

- “People figure out their F-35 symptoms, essentially by flying it, as odd as that sounds.”
- “This isn’t the hypoxia that you were trained to in UPT, you pull your green ring, or you turn the BOS on, it’s a green knob in this aircraft, and you’ll *instantly* feel better, kind of like you get in the altitude chamber, but this may be a - then kind of let things settle out for a few minutes and then you should feel better over time but it might require minutes to address the situation and feel better.”

Cluster 5: Normalization of deviance.

There is a large body of literature on normalization of deviance (Vaughan, 2016). In operation, deviation from planning, expectations, procedures, and execution is common in most environments. Ideally, these deviations are detected and assessed for acceptance into operation. If acceptable, these deviations are used to improve the standard and folded into new policies and procedures that better suit the needs of the person-task-environment. Alternatively, these deviations are considered unacceptable, adherence will be emphasized. The failure to address identified deviations allows expectations to become informally set and influenced with an inherent cost of an unquantified risk acceptance.

Some areas listed above included elements that were potentially contributory in increasing the threshold for pilots detecting deteriorating conditions that could have served as early warning of an unstable system prior to pilot injury or physiological event. Several pilots used word choices such as "new normal", "normal normal", and "nonevent" to describe the different sensations and impact perception capabilities.

First, previous software versions in the F-35 yielded prevalent OBOGS fails. The report refrains from comment regarding the accuracy of these notifications nor sensitivity of the system. The prevalence of these ICAWS were addressed in a software change, but in the interim, program guidance to the pilots modified pilot perception of the severity of this warning. In one incident, a pilot indicated he was notified of an OBOGS problem and went on the BOS, as dictated by the procedure. Unfortunately, as reported earlier, hypoxia recognition training does not accurately provide the expectation that symptoms may continue for some time before improvement. So, during the first few minutes on BOS, his condition continued to degrade. He misattributed his issue to be with the BOS and went back on the (actually) faulty OBOGS.

Second, the known deviations in perceived breathing characteristics within the F-35 aircraft fleet reduced pilot identification of unsafe breathing conditions. The example provided is an aircraft with a 50% kinked OBOGS hose. The test pilot detected this aircraft as a "very bad breather" during the fit-to-fly check flight and reported concerns to relevant individuals. However, the pilot had no threshold guidance to identify when a bad breather should be considered an unacceptable breather. Although the breathing experience was undesirable, it did not result in a PE; therefore, the pilot had no choice, but to sign off on the aircraft as fit to fly. There was no way to quantify the subjective sensation which might have led to the detection of the reduced functionality of the breathing line.

Quotes include:

- "Now thinking back and knowing how I respond in the jet now, how I feel in the jet now, that may also be incorrect. That may be something that's happening all the time now, and I'm just used to it with 500 hours or so now in the F-35."
- "It's important to emphasize these ICAWs, these OBOGS fails in the 2B software that we were flying at the time, these happened all the time like it was considered a nonevent. In fact, depending on what software subset you had of the software subset you could actually just continue the sortie [after the ICAW cleared]."

Cluster 6: Pilots expressed several concerns related to the organizational or leadership elements related to the F-35.

The beginning of this section contains comprehensive statements made by the pilots. These statements typically included significant concerns related to responsiveness and considerations for the pilot. Human are typically able to adjust and compensate for a wide range of flawed designs. Unfortunately, this accommodating feature can obfuscate the importance of the human element, attributing the successes, instead, to the technological development. Accurate and sufficient testing much be conducted to determine likelihood of success for any system. With large, dissociated programs, unintended outcomes can occur even from small, simple, or seemingly meaningless modifications to design or protocol as occurred in Apollo 1. Close examination by individuals with appropriate expertise is required for modifications.

Quotes include:

- "The F-16 had some significant growing pains as it was introduced as far as there were medical factors, it was routinely killing pilots with GLOC and spatial disorientation, but that was several decades ago. With time, effort, investigation, a merging of aerospace and aeromedical efforts, these were overcome and went on to become one of the most successful fighters in history and I'm confident the F 35 will do the same."

- "There was tremendous amount of concern amongst the [F-35] enterprise that the program was vulnerable, at the time, and so there was a lot of pressure to continue testing, continue pressing forward. The team as a whole, and especially the program office folks who were in charge of the life-support system at the time, were fairly motivated to assign any, or my symptoms, I guess, my actual reaction, to something that was not attributed to the jet, I guess was their aim. That was my perception, was that that was what they were trying to do: find a way to have it not be the jet so they could press."
- "We talked our way through it and I advocated for an investigation of the design of the system, because, at least it seemed clear to me that, the system even if it had functioned as designed… and that was a rapid conclusion, that they evaluated how everything worked; all the equipment in the chain from OBOGS and BOS through the PIC through my mask to me everything had functioned as it was designed to and so my concern was if they had designed it to do THIS and not protect me from hypoxia in this sort of a scenario, then we had a problem with the design that we should evaluate where those problems were. At the time there was a significant amount of resistance to doing that, again, their assessment was: it worked as designed, the oxygen system wasn't broken, it was a bleed air problem. No need to continue any investigation into the design of the system, as far as it being available in an emergency where there's no bleed air available for pressurization air or for the pilot."
- "I learned a lot of words that I didn't know before. Besides hypoxia, they discussed that they thought maybe it was hyperventilation. And maybe not hyperventilation in the sense that I was breathing too often and too shallow, but because I was actually actively trying to control my depth and rate of breathing that I had over-controlled and therefore induced hypoxia symptoms by a sort of self-induced hyperventilation. That was one theory. They also, I learned a word called hypercapnia… they were able to, again, sort of talk themselves into using those words and saying "well, maybe it was hypercapnia, maybe it was hyperventilation, but in no case is it something we need to change the design."

2.2.3 Pilot Interview Conclusions

The excerpts from F-35 pilot interviews, above, suggest that there a number of problems with the F-35. A more comprehensive record of the pilot interviews is included in Appendix 7.1. The breathing experience in the aircraft is unlike anything these pilots had experienced before. The F-35's breathing system noticeably discourages the normal breathing function via high-pressure, pressure surges, and hyperoxia. However, the pilots' desire to fly this new fighter, despite the abnormal breathing experience, has led them to try and adapt as best they can both autonomically and cognitively. A mismatch between pilot expectation of the performance of a system and that system's actual performance can provide warning of a potential problem. However, if the observed system performance continues to deviate from expected without formal assessment or protocol correction, expectations will recalibrate to consider the deviated performance as normal. This modifies the importance assigned to the system deviation and reduces the effectiveness of the warning system. This normalization of deviance can undermine the safety of mission, a pilot, and an entire program. Even flying the F-35 on routine sorties has led to symptoms that include dizziness, cognitive confusion, and severe fatigue. Some pilots who report the onset of hypoxia indicate that is markedly different than hypoxia awareness training. As difficult as the F-35 breathing system is, it can vary significantly between aircraft as described later in this report. Finally, despite highlighting these issues and requesting that the design of the F-35 breathing system be investigated, a number of the pilots interviewed believe that there is undue pressure to ascribe breathing problems to pilots and suppress information about these problems.

2.2.4 Humans and the System-of-Systems Approach

Disciplines such as Human System Integration and Human Factors are used to ensure safe and effective performance outcomes of tools, systems, interfaces, and/or procedures through the comprehensive application of the limitations, expectations, and tendencies of the intended user/population (Sharit, 2012). Human error is frequently cited as the cause when performance is judged as unsafe or ineffective. Responsibility for that error is commonly assigned to the "closest" individual related to that error, the person at the "sharp end," rather than examining the situation within which the human was required to operate to understand the why and how.

Error does not occur in a vacuum (Reason, 1990).

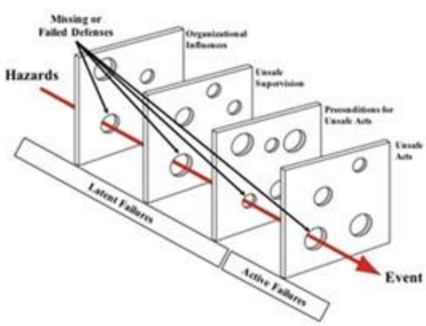

Figure 2.1. The Swiss Cheese Model of Accident Causation (adapted from Reason, 1990)

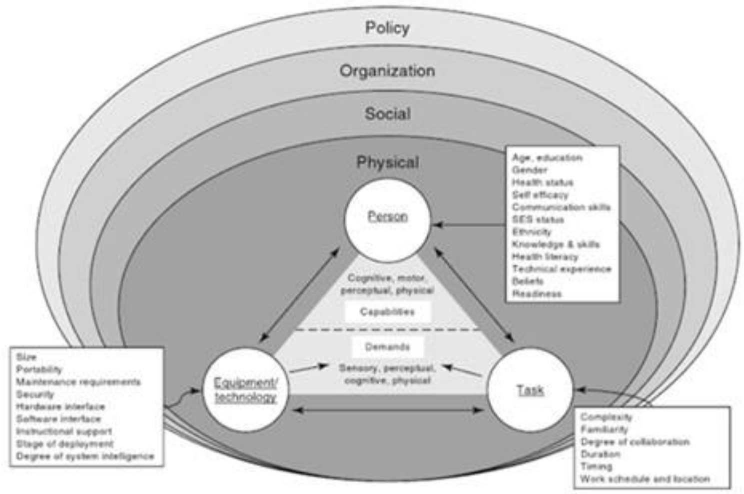

Figure 2.2. Human Factors Model of Person-Task-Equipment System (Czaja & Nair, 2012)

A system-of-systems approach enables the exploration of the interaction of many components. The person-task-equipment triad exists within the physical, social, organizational, and policy environment (Czaja & Nair, 2012). Contributing factors for any event must address every point between the dull end and the sharp end including "those responsible for conceptualizing and designing the artifact; those responsible for installing, maintaining, or providing instruction on its use; those who determine and oversee the rules governing its use; or those who actually use it." (Sharit, 2012). This framework clarifies that the unwanted event or outcome considered as human error was simply the natural outcome of the culmination of events. That, given the situation, there is increased likelihood that any person would perform the same way. Numerous frameworks are available to assist during this decision-making process with proper training for implementation. One such is the Human Factors Analysis and Classification System (HFACS) by Shappell & Wiegmann. This technique is currently used by the services for accident investigation, but are also extremely beneficial to identify the root of the problem.

Avoiding further undesirable events cannot be accomplished without addressing latent factors that induced the undesirable event. Outcomes assigned absent context will result in error management techniques that do not address the latent factors, do not improve the error rate, and potentially even yield unintended consequence (e.g., overpressurization). The thorough integration and application of disciplines related to the human in an operating environment will provide better solution identification. Without including the interaction of the human to the machine and environment numerous areas for improvement remain unidentified. Other comments not included in these clusters were related to the current flight crew equipment. In particular, that the combat AFE complement when flown in the long missions in combat, is reported as extremely problematic. Statements such as these along with bodily pain associated with the ergonomics of the F-35, though not within the scope of this report, are stressors on the body. A serious examination of the pilot experience in this aircraft should be conducted with the understanding that the human can be pushed beyond the ability to perform by numerous small insults as easily as a few large insults. No task is without disadvantage, but there is a limit to the reasonable expectation of a pilot to compensate and proceed without impact to task operation.

References:

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Vaughan, D. (2016). *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*, *Enlarged Edition*. University of Chicago Press. pp. 30–1.

3.0 Motivating Factors for F-35 Breathing Tests

In 2017, an F-35A at Hill AFB, Utah, was impounded and grounded after a Functional Check Flight (FCF) for difficulty breathing, cognitive disability, and breath times reportedly doubled from an average 5-second interval to a noticeably longer and repeatable 10-second interval. Lingering physiological symptoms including feelings of cognitive disability and extreme fatigue were present post flight. After investigation, the aircraft was discovered to have a significantly kinked tube delivering breathing O_2 from the On-Board Oxygen Generation System (OBOGS) to the breathing regulator. In the course of troubleshooting this problem, the regulator in this aircraft was replaced twice, followed by replacement of the kinked OBOGS feed line, when the faulty hidden line was discovered.

Extensive procedural and maintenance checks were accomplished with the aircraft running, and the aircraft was released from impound after the new breathing line was installed and checked. During these checks, it was noted that multiple factors appeared to be repeatedly affecting breathing dynamics, most noticeably breathing times. This observation prompted further investigation to characterize and understand the phenomenon of varied breathing times. Measured breath times at various settings can be seen in Table 3.1. Note that these measurements were taken in-flight after the identified kinked line had been replaced, the regulator had been replaced, and all maintenance checks performed during a dedicated FCF flight. The aircraft breathing system was fully “operational” during these measurements, and as such was expected to be representative of a nominal F-35.

Table 3.1. Hand Collected Data of Measured Breath Times and Respective Condition for Hill AFB F-35A

Approximate Altitude in MSL	Cabin Pressure Altitude	Condition Setting	Measured Time to Complete 10 Breaths
39,000 MSL	15,800 CP	Military Power	63 seconds
38,000 MSL	14,900 CP	Military Power + Defog	82 seconds
38.000 MSL	15,300 CP	Idle Power	59 seconds
30,000 MSL	11,200 CP	Military Power	66 seconds
30,000 MSL	10,700 CP	Military Power + Defog	76 seconds
30,000 MSL	11.500 CP	Idle Power	56 seconds
20,000 MSL	08,100 CP	Idle Power	56 seconds
20,000 MSL	08,100 CP	Military Power + Defog	68 seconds
15,000 MSL	14,500 CP	250 KCAS + Defog	45 seconds (Cabin Pressure Dump)
15,000 MSL	14,500 CP	250 KCAS	40 seconds (Cabin Pressure Dump)
15,000 MSL	08,200 CP	250 KCAS	37 seconds (No Mask/Mask-off)
15,000 MSL	08,100 CP	250 KCAS	58 seconds
11,000 MSL	10,900 CP	240 KCAS	40 seconds (BOS/Cabin Press Dump)

A typical mask-off breathing time for 10 breaths was 37 seconds (highlighted in yellow), and for the purpose of Table 3.1, this value was considered the baseline nominal breathing time. Also, note that many of these conditions show significantly longer measured times to complete 10 breaths, in some cases more than doubling the baseline 37 seconds. This is indicative of the aircraft significantly altering the pilot's breathing. The Defog setting (detailed later) was a consistent factor in significantly increasing breathing time, correlated with a significant backpressure sensation reported by the pilot. The cabin pressure dump setting ameliorated the prolonged breathing dynamics, again correlated with pilot reported decrease in backpressure sensation. These data were unexpected and led to the collection of the higher fidelity data presented in this report, which were intended to help understand and characterize those factors.

4.0 Dedicated F-35 Ground Check

In January 2018, Colonel Kevin "Sonar" Hall received permission from the appropriate authorities (including the local JPO representative) to take pilot breathing measurements using a VigilOX in two F-35s. Colonel Hall, an F-35 pilot, developed the measurement regime and took data with himself in the cockpit. The data was taken while both aircraft were on the ground with engines running. The data was subsequently embargoed by the Air Force. Later, in May 2018, the PBA team stood up with Colonel Hall as a member serving as a subject matter expert. Approximately one year later, the PBA Lead (C H Cragg) requested this F-35 data from the Air Force be made available to the PBA team for analysis. After some delays, the Air Force provided the requested data. The analysis in this report comes from this data.

4.1 Data Collection Setup

In January 2018, data were collected to compare two F-35A aircraft during performance of a scripted ground profile. The aircraft configuration, pilot, day, and measurement device remained constant between the two test observations to ensure adequate comparison capability. This setup was approved for ground testing only and no airborne data was available for examination.

4.1.1 Aircraft

Two F-35A aircraft, tail numbers 11-5021 (Aircraft 1) and 12-5042 (Aircraft 2), were used for the data collection effort. Both aircraft were airworthy with no grounding maintenance pending.

4.1.2 Subject

One pilot was used for this data collection. The pilot was male, 41 years old, and in good health on flying status. He was an F-16 and F-35A/B/C test pilot current and qualified for flight on the F-35A at the time with 4 years/300 hours flight experience in all variants of the F-35. He was also an Instructor Pilot and Functional Check Pilot with approximately 18 years flying experience in 35+ aircraft with 2,400 hours of high-performance aircraft flight time.

4.1.3 Data Measurement System Description

The pilot breathing data was collected using a Cobham VigilOX™ Integrated Aircrew Equipment Physiologic Monitoring System prototype. VigilOX is an integrated suite of synchronized measurement sensors and represents the third generation of device development. The development of these sensors was guided by USAFSAM (USAF School of Aerospace Medicine), the US Navy, and NASA to meet the performance parameters and attributes required for in-flight physiologic measurements and safety of flight.

The ISB was connected in-line with the existing breathing supply hose going to the pilot's O_2 mask (Figure 4.1). The ISB attached to the front of the F-35 flight jacket and situated at the center of the chest between the Life Preserver Units. The breathing supply hose from the mask connects to one end of the ISB, in-line with the breathing hose that connects down to the PIC (Pilot Interface Connection) at the regulator. This position provided no interference with cockpit operations and no impact to breathing gas flow. The ESB was attached on the side of the vest using existing attachment points aft of the main vest pocket (Figure 4.1). A flexible breathing tube is attached to the exhalation valve on the O_2 mask and connected to the ESB sensor location on the side of the vest. The stock mask exhalation valve vents directly to the aircraft cockpit cabin, however, the ESB uses a hose to capture the exhaust breathing gas flow and redirects it down the ESB block for measurement.

Figure 4.1. Locations of the VigilOX Inhalation Sensor Block (ISB) and Exhalation Sensor Block (ESB) on the Pilot

The PBA's use of prototype versions prior to delivery of production versions during the assessment allowed comparisons of data quality between F-35, production, and prototype data quality. The F-35 data was comparable to PBA data. For this assessment, the ISB build version used was: ISB_DEV003, Software V0.24. The ESB build version used was: ESB_EDEV05, Software V0.12.

The majority of this analysis relies on mask differential pressure, ISB and ESB line pressures and flows, the most reliable sensors. Despite the extensive consideration given to known data reliability issues, some individual data artifacts presented in this report may be due to signal or processing errors. Due in part to the noted limitations in measurement and small sample of two aircraft, it is the intent of the NESC team that this analysis be treated as a compelling preliminary identification of potential problems in the F-35's breathing system which should serve as a motivation for more comprehensive testing.

4.1.4 Technical Description of F-35 Life Support System and Data Collection Setup

The F-35 is the most advanced fighter in the United States aircraft fleet, and as such has many new systems which are unique to the F-35. For aircraft in general, the systems directly responsible for a pilot's breathing may be divided into two categories, the Environmental Control System (ECS), responsible for maintaining the cabin environment, and Life Support System (LSS), responsible for delivering breathable air to the pilot via a mask. For the F-35, the ECS exists as a subset of the Power and Thermal Management System (PTMS), and provides pressurized air to the aircraft cockpit via engine bleed air, as shown in Figure 4.2.

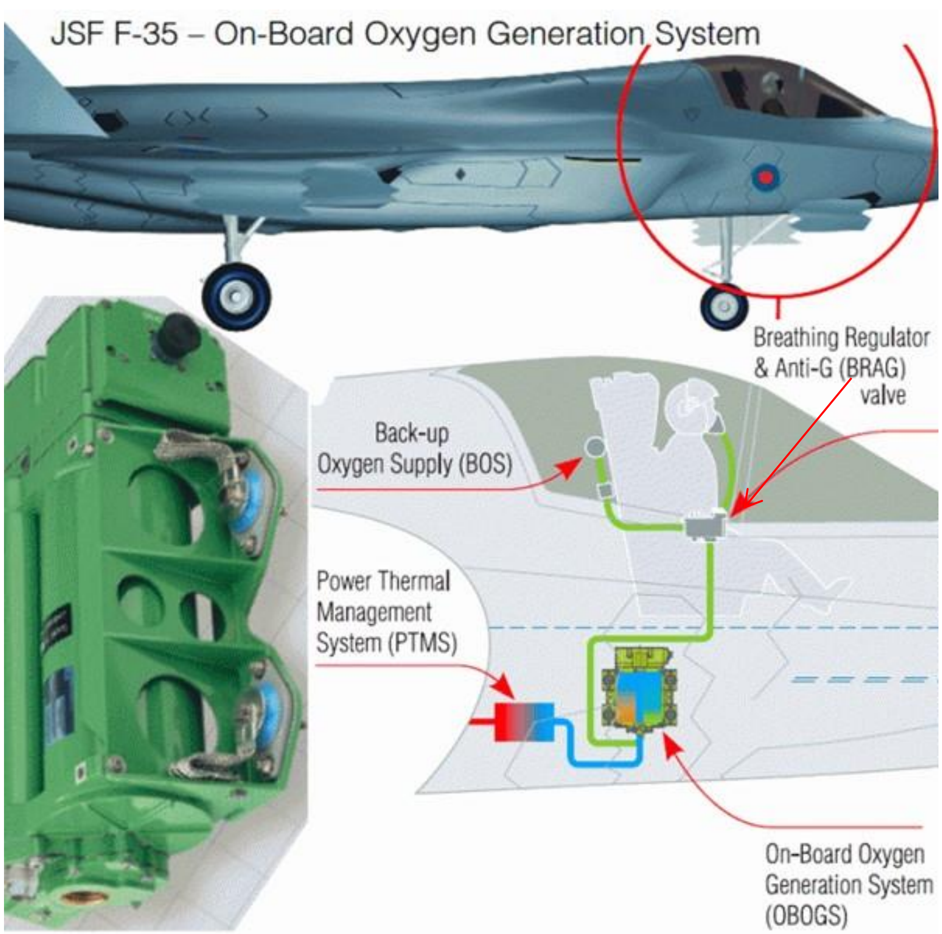


Figure 4.2. General Layout for F-35 Life Support System (Image from Google)

The Life Support System (LSS) of the F-35 consists of multiple components, starting with an On-Board Oxygen Generation System (OBOGS) which is fed engine bleed air. The OBOGS then uses a dual-bed 13X zeolite sorbent to remove nitrogen (N) and concentrate O_2 via a swing cycle shown in Figure 4.3.

A.11 F-35 Lightning II *Figure A-11. F-35 On-Board Oxygen Generating System.*

The F-35 OBOGS (Figure A-11 below) uses two immobilized 13X zeolite beds to generate the oxygen enriched breathing gas. Like the F-22 system, the F-35 controls dilution as a function of cabin altitude by controlling the charge-purge cycle times of the molecular sieve canisters. Both inlet and outlet filters protect against 0.6 micron particles. A seat-mounted BOS provides automatic fill-in to complement OBOGS during flight transient conditions and is automatically selected during ejection. This BOS obviates the need for a separate EOS. The unit size is approximately 16 x 15 x 5 inches. http://www.foia.af.mil/shared/media/document/AFD-120913-052.pdf

Figure 4.3. General Overview of F-35 OBOGS system (Image from Google)

O_2-enriched breathing air is fed through a Breathing Regulator and Anti-G (BRAG) system, through a Pilot Interface Connection (PIC), and into a mask fitted to the pilot’s face. The BRAG system in the F-35 is of particular note since it is a completely electronic regulator (as opposed to mechanical), representing the very first of its kind to be fielded in an American fighter aircraft. The BRAG feeds both the breathing air to the pilot’s mask and the air supply to inflate/deflate the pilot’s G- suit. The F-35 uses Positive Pressure Breathing (PPB) for G and for altitude, but does not utilize a chest counter-pressure garment. The F-35 OBOGS attempts to keep O_2 concentration within the range specified in MIL-STD-3050, and schedules O_2 enrichment based on altitude. This BRAG is manufactured by Air Liquide, a French partner company. These systems have undergone extensive centrifuge and altitude testing. From discussion with F-35 engineering and maintenance personnel, the internal workings of the BRAG are not well understood, and were not declared as a contract deliverable at the time that the BRAG was designed and integrated.

The pilot mask used in the F-35 is the same basic mask (MBU-20/P) which is used in all other fighter/trainer aircraft and uses the same inhalation/exhalation valve set. Differences include the addition of an anti-suffocation valve and a different microphone.

4.1.5 Test Procedure and Conditions Description

The two F-35 ground tests were performed on January 18, 2018 and January 22, 2018 at Hill AFB, UT. Breathing data was gathered by the same experienced F-35 test pilot, at the same location, with the same climate conditions, the same flight equipment, and the same basic script from two different stationary F-35 aircraft with their engines running during normal ground operations.

The pilot collected data under intentionally relaxed breathing, at pre-determined conditions (Tables 4.1 and 4.2) for approximately 1 minute each. The Aircraft 1 vs. Aircraft 2 test conditions were made as similar as possible, so the primary variable was the aircraft. Talking and physically moving around inside the cockpit influences nominal breathing patterns; therefore, activities that change breathing patterns were intentionally avoided during the one-minute acquisition intervals. Additionally, effort was made to avoid "fighting" the aircraft by intentionally modifying nominal breathing; though, breathing impacts as forced by the aircraft systems cannot be entirely avoided.

The script in Tables 4.1 and 4.2 were performed in each aircraft at the indicated times, and the VigilOX data recorded.

Table 4.1. Timeline and Description of Ground Test Events for F-35 Aircraft 1

Event Descriptions for Aircraft #1	Start Time	End Time	(Events)	(in File)	Start Value
#1 Normal relaxed breathing	15:28:00	15:30:07	1800	3000	#1-1800
#2 2x Max Inhale/Relaxed Exhale	15:30:07	15:30:25	2400	3400	#2-2400
#3 Backup Oxygen System (100% O_2)	15:30:31	15:31:49	3800	5000	#3-3800
#4 Defog Full On – Defog Full Off	15:31:58	15:34:33	7000	8400	#4-7000
#15 Time to take 10 breaths (10 clean regular breaths)	15:35:53	15:36:33	9600	10800	#15-9600
#5 Press to Test (PTT) [Increase in Mask Pressure/Flow]	15:36:45	15:36:57	10800	11200	#5-10800
#5 Press to Test (PTT) [Increase in Mask Pressure/Flow]	15:37:11	15:37:25	11500	11750	
#6 G-Suit Disconnect [Disconnected for next 8 minutes]	15:37:25	15:38:25	12500	22000	#6-11800
#7 PTT (G-Suit Disconnected)	15:38:25	15:38:40	12950	13250	#7-12800
#7 PTT (G-Suit Disconnected) cyclic blocking of G-Suit manifold port	15:38:47	15:39:05	13400	13750	
#8 2x Max Inhale/Relaxed Exhale (w/o G-suit)	15:39:26	15:39:39	14150	14450	#8-13800
#8 Rapid deep breaths	15:39:39	15:39:50	14450	14650	
#9 Normal relaxed breathing	15:40:00	15:41:51	14800		#9-15400
#10 Defog (G-Suit Disconnected)	15:41:51	15:42:28	17200	17800	#10-16900
#11 Mask Off (G-Suit Disconnected)	15:42:45	15:42:57	18150	18400	#11-17800
#12 Engine Thrust (ETR) 15%	15:43:22	15:45:37	18800	21000	#12-19300
#13 G-Suit Connected	15:45:37	15:46:07	21000	22000	#13-20500
#14 Press to Test (PTT) using BOS	15:46:07	15:46:16	22200	22400	#14-22000
#14 Press to Test (PTT) using BOS	15:46:25	15:46:32	22600	22750	
#14 Press to Test (PTT) using BOS (G-Suit Disconnected)	15:46:40	15:46:46	22850	22950	

Table 4.2. Timeline and Description of Ground Test Events for F-35 Aircraft 2

Event Descriptions for Aircraft #2	Start Time	End Time	(Events	(in File)	Event Start
#1 Normal relaxed breathing	18:10:00	18:11:28			#1-3000
#2 Mask Off	18:11:28	18:11:49	4400	4850	#2-4300
#2 2x Max Inhale/Relaxed Exhale	18:12:08	18:12:17	5200	5400	
#3 Backup Oxygen System (BOS)	18:12:24	18:13:29	5500	7000	#3-5800
#4 Defog	18:13:29	18:14:29			#4-7200
#5 Mask Off			8400	8750	#5- 8400
#5 Press to Test (PTT)	18:15:31	18:15:42	9250	9500	
#6 G-Suit Disconnected	18:15:54	18:16:56	9900	11100	#6-9900
#7 PTT (G-Suit Disconnected)	18:17:12	18:17:22	11250	11450	#7-11000
#7 PTT (G-Suit Disconnected) cyclic blocking of G-Suit manifold port	18:17:37	18:17:53	11750	12100	
#8 2x Max Inhale/Relaxed Exhale (w/o G-suit)	18:18:00	18:18:12	12250	12500	#8-12100
#9 Rapid, deep breaths	18:18:45	18:19:08	13150	13600	#9-13100
#10 Defog (G-Suit Disconnected)	18:19:05	18:20:06	13700	14950	#10-13600
#11 Mask Off	18:20:16	18:21:32	14950	15450	#11-14800
#12 Engine Thrust (ETR) 15%	18:20:37	18:21:50	15550	17000	#12-15800
Backup Oxygen System (BOS)			17100	19300	
#13 Press to Test (PTT) using BOS (G-Suit Disconnected) cyclic blocking of G-Suit manifold port	18:22:08	18:22:25	17200	17550	#13-17000
#13 G-Suit Connected	18:22:25	18:23:38	17600	18800	
#14 Press to Test (PTT) using BOS	18:23:38	18:23:48	19000	19200	#14-18200
#15 Mask Off (Unusual difficulty starting flow)	18:24:15	18:25:15			#15-19900

5.0 Breathing Dynamics

5.1 F-35 Pilot Interview Comments on Breathing

The F-35 interviews were consistent in their observation that the breathing dynamics of the F-35 are different compared to other aircraft. Pilots described breathing in different ways:

- “It does breathe differently. It was something that I got used to relatively quickly, and poor test piloting on my part because I adapted to the airplane, and didn’t make good note of that adaptation. In hind sight there certainly is a threshold of initiation of the breath that the pilot has to do. So it kind of doesn’t do anything until you breathe in past some certain threshold, and then you begin getting flow, so there’s this general breathing technique I learned, and it was more subconscious than learned, where I would initiate the breath, then breathe while I have flow, and then you kind of have to exhale a little bit more forcibly and then that sort of stops and resets the valves, and then you can finish the exhale process. It definitely takes more attention, whether subconscious or conscious to breathe in the F-35 than it does in any of the other airplanes that I flew, including ones that I did fly the F-15 with OBOGS and F-18 with OBOGS, and I don’t remember those having any need to adapt my breathing like I had to in the F-35.”
- “What I do know is that breathing in the F-35 is different. Breathing in [Strike Eagle] off of an MSOGS was a different experience than it is breathing out of the F-35. The F-35 is different in the fact that it has positive pressure all the time, not just pressure breathing for G but positive pressure in the mask. It’s different in the fact that the ECS environmental control system in the F-35 sometimes surges, sometimes pulls back. It’s a different physical environment that you’re in and the breathing is different.
- "It's the new normal. Breathing in this jet is different than sitting here talking to you and breathing. It shouldn’t be, in my opinion, but it is."
- “Sometimes the F-35 just provides a whole bunch of pressure into the mask for unknown reasons, I don’t know why but it does, it makes exhalation difficult”

- "And then sometimes [the expiratory pressure] will change in the same expiration, like you'll be expiring, against a certain expiratory pressure and then it'll kick back at you sometimes or sometimes it'll go away and it can be somewhat variable, even within the same respiratory cycle. 35 things."
- "When you're breathing off the mask in the F-35 you feel like you have to work a little bit harder so you're a more forceful inhalation, sometimes, you have to more forcefully exhale"
- "The positive pressure isn't really, in my thinking, isn't so positive. It can be annoying."
- "Sometimes even in a single exhalation there could be a change in the pressure. So there's like a kick back and it can actually bite off a radio call."
- "You're exhaling against a constant pressure but then it'll kick back whatever pressure you're using to exhale and speak, and that pressure is equalized ceasing your exhalation and ceasing your vocalization for the radio transmission."
- "you'll be talking and then as you're talking your expiring and you're anticipating certain expiratory pressure as you're talking but within the same exhalation while you're talking, sometimes it will kick back and it will literally just like (mimes inability to exhale) like stop your expiration and it'll just, like, cut off your exhalation and talking concurrently, or as a secondary effect, and then you have this oddly clipped radio call."

5.2 Hysteresis: Definition and Examples in the F-35 Breathing System

Hysteresis is usually understood as a lag in a mechanical system, or the reluctance/inability of a dynamic system to return to a previous state once perturbed. A system demonstrates hysteresis if it does not return to its original rest state along the same path on which it went out, or if the system takes longer to return from a dynamic state than it did to reach the state initially. Test pilots may be familiar with the concept of hysteresis in aircraft controls or avionics systems. The analysis of PBA data shows that the concept of hysteresis applies and is a significant factor in the performance of pilot breathing systems.

Ideally, the aircraft breathing system will respond to pilot demand pressure quickly, reliably, and in proportion to the demand. Figure 5.1 shows three consecutive inhale breaths from a PBA test flight in an F-18 aircraft. The jet breathing system was in a USAF CRU-73 diluter demand panel mounted configuration, so it did not have safety pressure. The graph shows the inhale flow as a function of the differential pressure of the regulator outlet and the cabin,

$$\Delta P_{l-c} = (P_{line} - P_{cabin}).$$

The start and end of an inhale are indicated by the open triangle and closed circle, respectively. Each datum point represents a time increment of 0.05 sec and the arrows represent the path taken from the start of the breath to the end of the breath. The three breaths are from a part of the test while the F-18 aircraft was still on the tarmac before takeoff.

NASA F-18 with diluter demand regulator

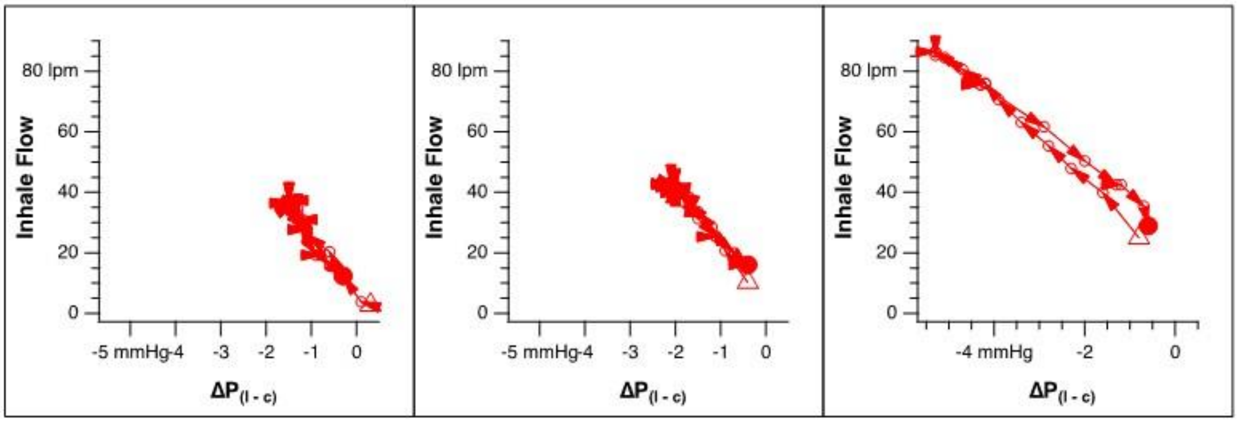


Figure 5.1. Inhale Flow vs Regulator Outlet Differential Pressure for a NASA F-18 with diluter demand regulator; showing nominal hysteresis. Note the linear relationship between flow and demand pressure over time.

There are several significant points of note from these breath plots. First, breathing flow varies very linearly with the pressure differential. The flow from the regulator is in direct proportion to the demand signal on the regulator. Further, the regulator response is the same from breath to breath; the system reliably produces the same flow for a given demand. Finally, there is no appreciable lag or hysteresis in the system; the flow from the regulator is only a function of the demand signal and not dependent on whether it is in the beginning, middle, or end of the pilot inhale cycle.

Figure 5.2 shows a sequence of three breaths during relaxed breathing (the same pilot as in Figure 5.1) in an F-18 only this time in a USN chest mounted CRU-103 configuration with safety pressure. In this case there is an offset in the differential line pressure (x-axis) corresponding to the safety pressure. The data show that the path for the inhale is now oblong (non-linear) rather than a line (linear), and does not trace the same path back and forth as the pilot's breath pressure changes with time, with a different return path than the "out" path; in other words the breathing pattern is displaying hysteresis.

NASA F-18 with Safety Pressure Regulator

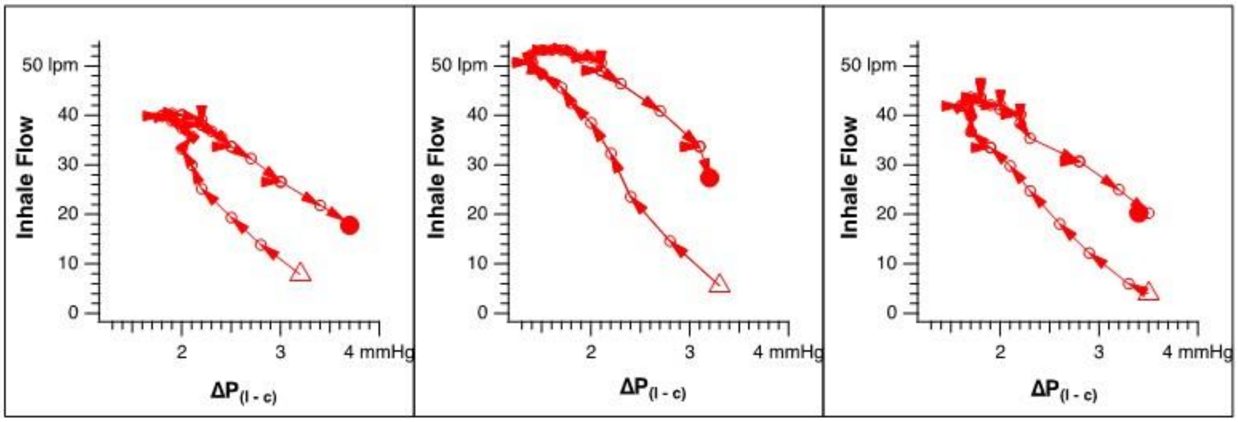


Figure 5.2. Inhale flow as a function of line-cabin differential pressure for NASA F-18 with Safety Pressure Regulator; showing pressure and flow hysteresis, with flow lagging behind pressure early. Later in the breath, flow exceeds demand.

While the breathing system in Figure 5.2 is not ideal, the path traced by the breath is still very smooth. There is a predictable relationship between the flow of air supplied to the pilot, and the pilot's demand. The PBA data show that pilots can breathe on a demand safety pressure system like that in Figure 5.2 safely as long as the hysteresis in the system remains relatively low.

This oblong path is symptomatic of the lag inherent in a demand system without a diluter function. Because the regulator is sensing the signal at a finite distance from the pilot (the length of the mask and hose), and has mechanical springs and bellows regulating the mass flow response, it cannot respond instantly to changes in the demand signal. In a demand regulator system, unlike normal breathing on the ground, there will always be a delay between the initiation (the request for air), the regulator response, and the resulting flow reaching the pilot's mask. Diluter systems minimize this problem. The dilution allows instant access to a large volume of unrestricted (cockpit) air to backfill for the delay or compensate for regulator restriction. Significant loss or delay in this process results in flow that is not directly proportional. During the first half of the breath where demand is increasing, a delay results in less flow than demanded in any given instant, which is why the oblong path is lower at first. Conversely, when a pilot is decreasing their breathing demand during the second half of the breath, the lag causes the regulator to proportionally provide more flow until the responding flow drops to match the decreased demand for flow. The pilot has to work against the aircraft, being slightly undersupplied during the first part of the breath, and being slightly oversupplied during the second half of the breath. In summary, hysteresis makes it more difficult to start the flow (flow lags demand), and more difficult to stop the flow (flow exceeds demand). The hysteresis as seen above is too subtle for pilots to notice (i.e., the pilot is unaware that a machine is reading and responding to the pilot's needs, and subconscious respiration functions normally). However, past some point the divergence from open air breathing becomes apparent to the pilot, such as in the F-35, according to pilot reports.

- "You kind of have to begin the exhale as an event, and then once that all starts, and the flow begins, then kind of exhale normally. So, I guess another way to describe it, and this is not an accurate mechanical description, but the feeling was kind of that it was like a sticky valve, both directions. You, kind of, have to pull to get the inbound air going and then once the valve is flowing that I could breathe in with big continuous motion. And the same thing, I had to initiate the exhale, so a sticky valve feeling in that sense, and then once the exhale began, I could just go ahead and exhale normally."

Figure 5.3 shows a set of three consecutive breaths during a relaxed breathing period collected from a pilot breathing on an F-35. There is a chaotic relationship between pressure, flow, and time that is neither linear nor smooth. This demonstrates the pilot fighting the machine. The path is now extremely oblong, indicating a severe lag in the response of the breathing supply system. On each breath, the pilot demand increases at the beginning of the inhale, but the system does not initially respond at all. During the end of the breath when the pilot demand decreases, the supply remains high and the jet overcompensates pushing air into the pilot. Also notice that the path has become jagged, irregular, and inconsistent from breath to breath. This flow is highly inconsistent throughout each breath, with large variations in flow as the pilot breathes in and out. Because each breath is so variable and different it is difficult for the pilot's subconscious breathing to seek out and find a consistent breathing solution.

F-35 with electronic demand regulator

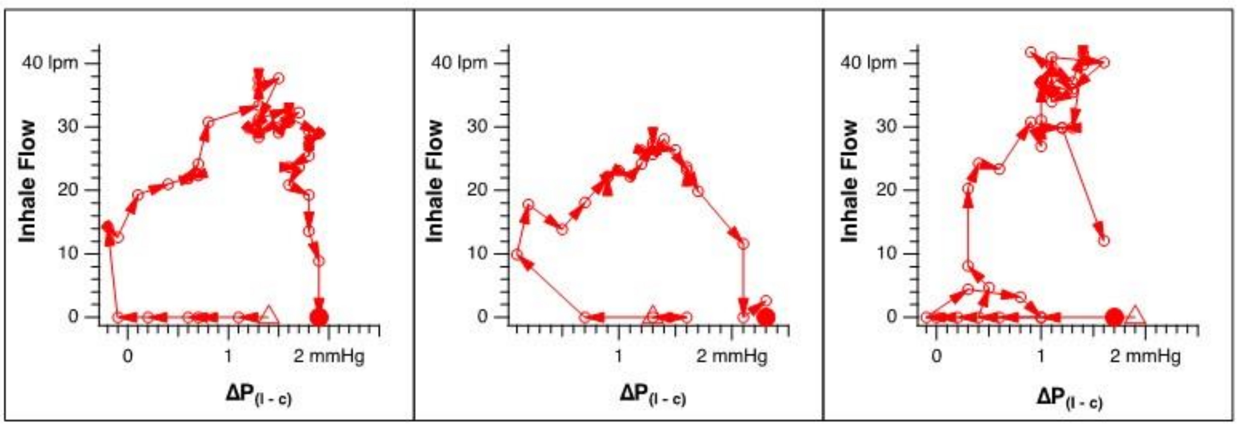


Figure 5.3. Breathing Pressure vs Inhale flow for F-35 aircraft, demonstrating severely non-linear path with extreme hysteresis and large amounts of deviation.

Early in a breath, there is no flow despite increasing demand. In the middle of the breath, flow is complex and overshoots demand. At the end of the breath, pressure remains high as demand drops.

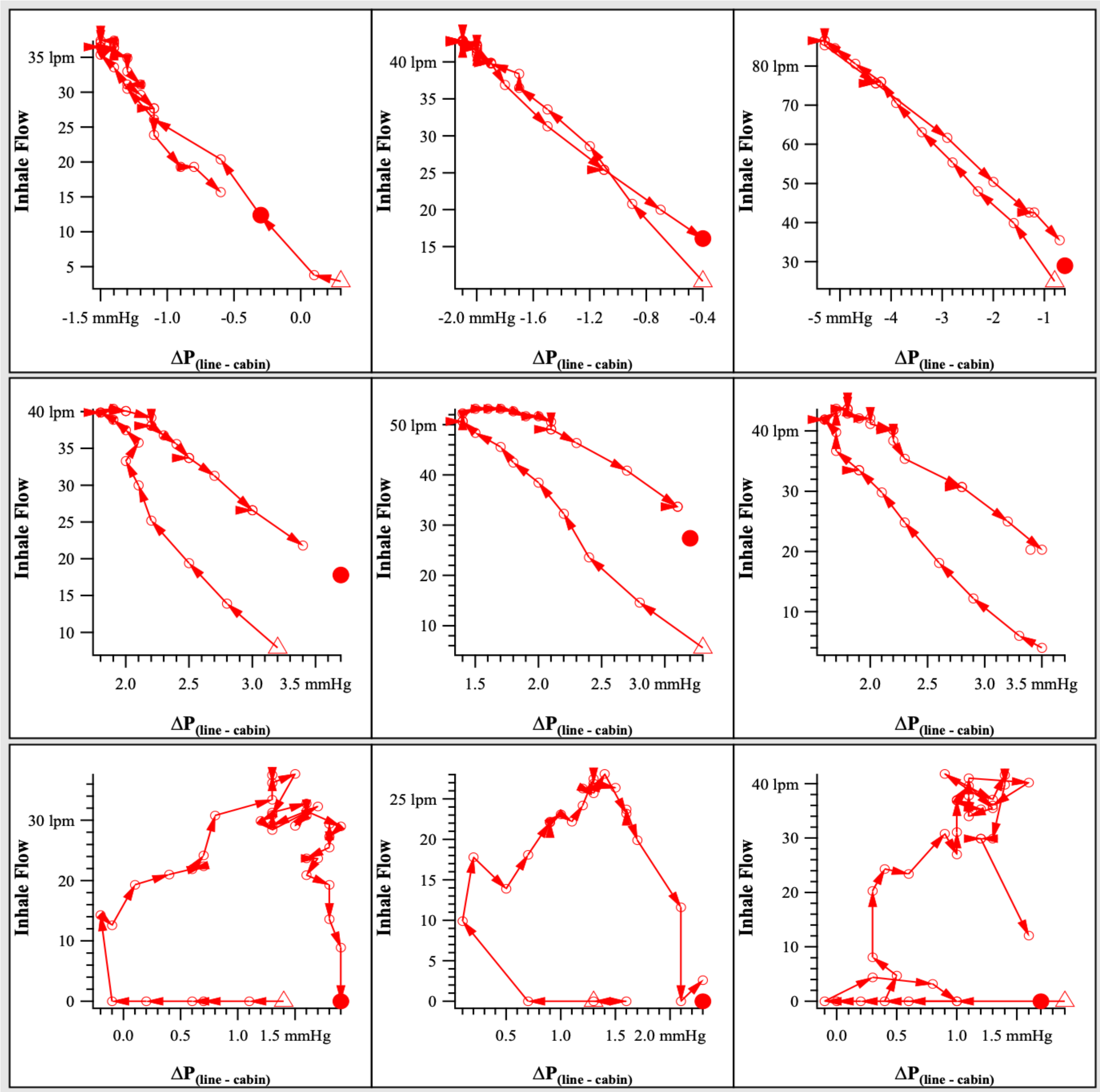


Figure 5.4. Comparison of hysteresis: (top) F-18 with diluter demand regulator (middle) F-18 with demand only and safety pressure (bottom) F-35 with demand only and safety pressure (figures rescaled to focus on hysteresis effect)

The data in Figure 5.4 show that at the beginning of each F-35 inhale the line is flat in stark contrast to the two F-18 regulators. The pressure drops with no corresponding increase in flow. The pilot is not just being undersupplied, as in the middle case with mild hysteresis, but is not receiving any flow at all initially. During the middle part of the breath the slope goes the wrong way, with both pressure and flow increasing. Normal human-generated breathing results in flows that increase proportionately with demand, and decrease with reduced demand. That is the environment for which our respiratory system is adapted and that is how diluter demand breathing systems operate. Simultaneous increases in flow and pressure result in overshoots of pressure during the second half of the breath. Note that pressure and flow are never in the top right corner for the F-18 data (Figure 5.4). The F-35 pressure and flow (Figure 5.4) in the top right corner of the graph signifies high flow with no pressure demand signal; this is physiologically important and will be discussed more in Section 8, medical, as excessive inspiratory pressure.

Consider this pressure-flow pattern in the context of lung physiology. The alveoli are tiny thin membrane balloons. Imagine the pressures in of these thin membrane balloons experience during inhalation. In the patterns observed, each breath is similar to sucking against a closed valve (no flow initially), followed by the valve quickly opening (rapid onset of flow), and the valve remaining open when it should be closing (over pressurization). This thin membrane in the lungs is exposed initially to outward pulling forces from all sides to open-up, however with no flow, it is as if the opening of the balloon were pinched off. The rapid onset of flow is analogous to a balloon popping open with air rushing in to fill the balloon to the position where the natural lung demand had been pulling it open. Lastly, the air continues to flow past the point of natural demand, forcibly overinflating the analogous balloon at an unnaturally high pressure for that size of balloon. This breathing pattern of starved flow initially, followed by a non-linear discontinuity (a pop or snap during opening), and then rapid over pressurization tending towards over inflation occurs with regularity in the F-35. This pattern is a stark contrast to the much smoother and near linear flow observed in the F-18/F-15. The energy imparted to these thin membrane balloons by rapid changes in pressure (up to 2 mmHg) without a change in flow, changes in flow (up to 20 LPM) with minimal change in pressure, and pressure oscillations exceeding the AIR-STD 4039 limits (see discussion in 9.2 & Figure 9.2) contain energy up to 2 orders of magnitude higher than observed in the F-18 (see discussion in 5.8 & Figure 5.19). The physiologic ramifications to the sensitive alveoli in the lungs, and potential for injury from continuous asynchronous pressure flow patterns are discussed in Section 8.

The data in Figures 5.1 through 5.4 are for relaxed breathing where the pilot's metabolic demand is minimal. The fact that the F-35's breathing system does not respond to pilot demand proportionally, quickly, or reliably for relaxed breathing should be considered highly concerning. The clear lack of a predictable, proportional relationship between demand and supply in (Figure 5.3) shows a system that will be very difficult to breathe on in general, and may introduce random and unpredictable effects. Breathing pressure-flow relationships in the F-35 are very different from those analyzed in the F-18. Whereas F-18 pressure and flows exhibit a linear relationship with a diluter demand regulator, or exhibit a small hysteresis with a safety pressure regulator, the F-35 in comparison to the F-18 undersupplies flow at the beginning of the breath, compensates abruptly, oversupplies flow at the end of the breath, and does not have a corresponding monotonic relationship between pressure and flow.

5.3 Mask Pressure Dynamics: Mask Pressure versus Line Pressure Graphs

Every time a pilot breathes, the mask cavity pressure changes and the mask/regulator system has to keep up with the changes. Figure 5.5 is an example of the mask pressure and line pressure from the regulator on the F-15. There are many nuances, and understanding the following figures are essential to understanding the issues discussed herein, so it is discussed here in detail.

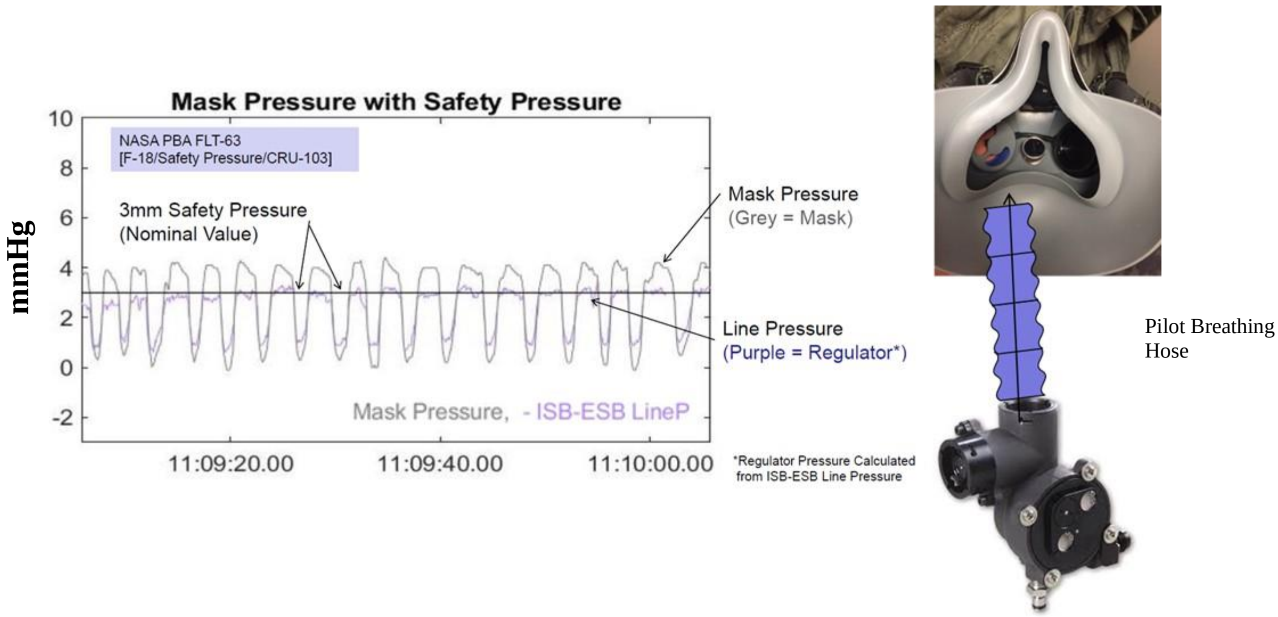


Figure 5.5. Ground data from a NASA F-18 demonstrating nominal mask pressure vs line pressure interaction. A CRU-103 Regulator, Pilot Breathing Hose, and Mask are shown on the right.

Figure 5.5 data was collected during PBA Flight #63, in an F-18 with the CRU-103 Regulator. The grey line in figure 5.5 represents mask pressure, which varies in this example from 0 to 4 mmHg during each breath. The purple line represents the line pressure from the regulator. The straight black line at 3 mmHg represents the nominal value (positive offset) of the CRU-103 safety pressure. Note the line pressure plateaus at approximately 3 mmHg (nominal safety pressure value) in-between each drop in pressure.

> **Note on Safety Pressure:** Safety pressure is a regulator design (or option on some) where the pressure delivered by the regulator is set at a value higher than the cabin pressure. Safety pressure is integral to the design of the regulator, set at a fixed value, and the mechanisms which maintain that pressure are involved in breathing dynamics. Higher safety pressures make inhale easier by pushing air into the lungs and make exhale more difficult as that same pressure must be overcome to exhale.

Each drop in pressure indicates inhalation, which results in a drop in the mask pressure and a corresponding drop in the line pressure. Note that the drop in mask pressure and line pressure track closely and smoothly together in a rounded-off "V" shape. As inhalation demand ends, and the inhalation valve is closed, the line pressure returns to its nominal safety pressure value and remains there at a relatively smooth and stable plateau. As the pressure rises during exhalation, the mask pressure increases to approximately 4 mmHg in this example and has a relatively smooth shape resembling an upside-down "U". The x-axis of Figure 5.5 is time; each graph displays a one-minute segment of breathing. The mask pressure is measured in the mask by the ESB. The line pressure is measured just after the regulator in the ISB. Note that the line pressure shown on the graphs is a differential pressure calculated by subtracting the ESB line absolute pressure from the ISB line absolute pressure (ISB-ESB line pressure). This is done in order to match the scale of the mask pressure, which is a differential pressure. In other words, the line pressure displayed is essentially the ISB line pressure minus the ambient cabin pressure. This derived measurement is fairly precise, but less accurate than the mask pressure. In this example, the breathing system is regulating and exhausting airflow in a relatively smooth, linear, and proportional manner as the pilot breathes, exhibiting the same characteristics as shown in Figures 5.1 and 5.2.

The breathing patterns of the two F-35 aircraft are shown in Figures 5.6 and 5.7. Both aircraft show distinctly abrupt waveforms, with significant oscillations and high rates of change during pressure swings. Additionally, the two aircraft traces are very different from one another. Oscillations exist during both inhalation and exhalation. The distinct troughs and peaks displayed in the F-18 (Figure 5.5) are notably absent. The exception is the mask pressure (grey) which occasionally exhibits a distinct trough. This trough has a rough "V" shape with frequent negative sharp downward pressure spikes at the beginning of inhalation. The degree of change between troughs is notable, having considerable variation in the magnitude of pressure drop due to the spike at the beginning.

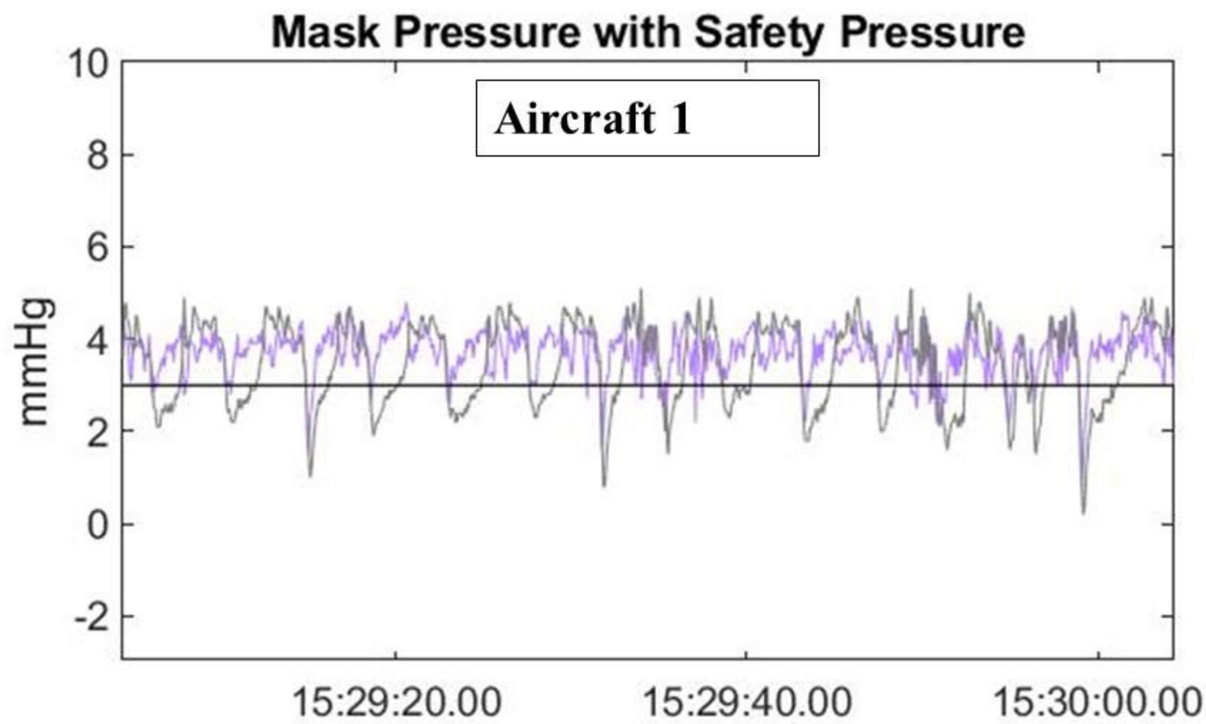


Figure 5.6. Mask Pressure (grey) vs Line Pressure (purple) from F-35 Aircraft 1

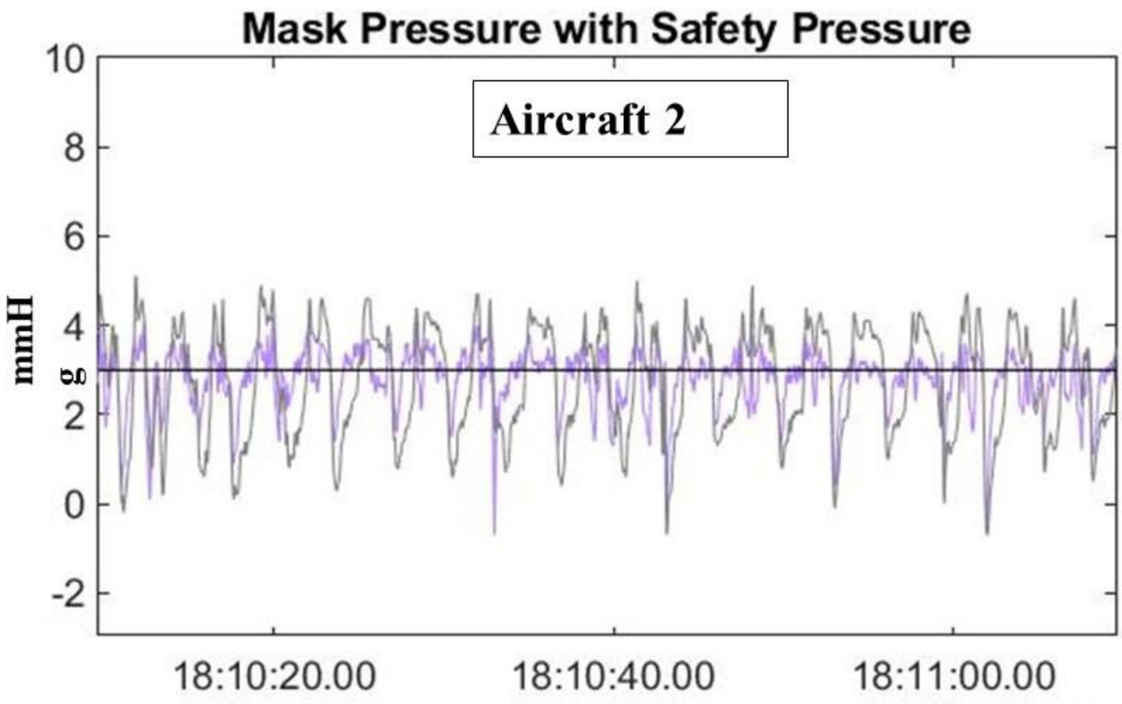


Figure 5.7. Mask Pressure (grey) vs Line Pressure (purple) from F-35 Aircraft 2

The lack of separation between mask pressure and line pressure during exhalation (above 3 mmHg) indicates that the pressure domains are communicating pressure when they should be isolated and independent. These rapid oscillations can also be considered as shock loading the alveoli, and they are observable by the pilots.

- "These oscillations are extremely prevalent and observable. If you unclick the mask from the helmet and hold the mask to your face, you can watch the mask move several millimeters during these pulses both during inhale and exhale. While the pulses during exhalation are annoying, and can cut you off mid-sentence, the pulses during inhalation are much more disturbing and have at times had an immediate physiological impact during deeper breaths. Kind of like a slight blow to the chest, which I guess the surge of air actually is in some respects. Said another way, it's like mid breath having the wind knocked out of you, or sucked out of you momentarily. Not pleasant."
- "Sometimes the F 35 just provides a whole bunch of pressure into the mask for unknown reasons, I don't know why, but it does. It makes exhalation difficult."
- "The backflow valve would get stuck sometimes. In fact, I remember there would be times I would reach up into the mask and punch the backflow valve if it got jammed. And then that would kind of leave you sometimes with a momentary shortness of breath sensation, I would say, maybe 1 in 10 flights you'll see that."

5.4 Pressure Oscillations: F-35 Breathing System During Exhale

The extreme oscillations present during exhale are circled in red in Figure 5.9. Both the mask pressure and the line pressure oscillate 1 to 2 mmHg. Normal breathing uses very little pressure differential: Exhale takes approximately 1 mmHg and inhalation approximately 2 mmHg. The pressure budget for moving air is very small. These oscillations superimposed upon otherwise normal breathing in Figure 5.9 are of the same magnitude as the pressures generated during normal breathing.

<u>Exhale Oscillations</u>: During exhale, the inhale valve should be closed, and pressure in the mask should be separate and independent from the line pressure, which itself should be constant at the safety pressure value. However, both the mask pressure and line pressure track the oscillations almost identically. This indicates the pressure domains are interacting and are not isolated from each other. Due to the compensation tube referencing the line pressure, the exhalation valve opens and closes as the pressure inside the compensation chamber increases and decreases with changes to the line pressure. Every increase in line pressure effectively increases exhalation resistance as the valve inflates and closes, and every decrease in line pressure effectively decreases exhalation resistance as the valve deflates and opens. The magnitude of change is large enough to be impactful: by comparison, in this segment, line pressures actually drop more during exhale than during inhale. Because the valve has a finite response time, as the pressure is changing, the valve is slightly more closed than it would be at steady state. However, as designed, the converse is not true; the exhalation valve cannot have less resistance than when fully deflated. This results in a one way ratchet effect, where oscillations can only increase resistance, but can never decrease resistance. These oscillations induce a breathing dynamic of highly variable exhalation resistance and higher than designed resistance with pressure changes exceeding the normal inhale and exhale pressures. This requires the pilot to consciously change breathing patterns to compensate, distracting them and contributing to fatigue or pulmonary micro-trauma.

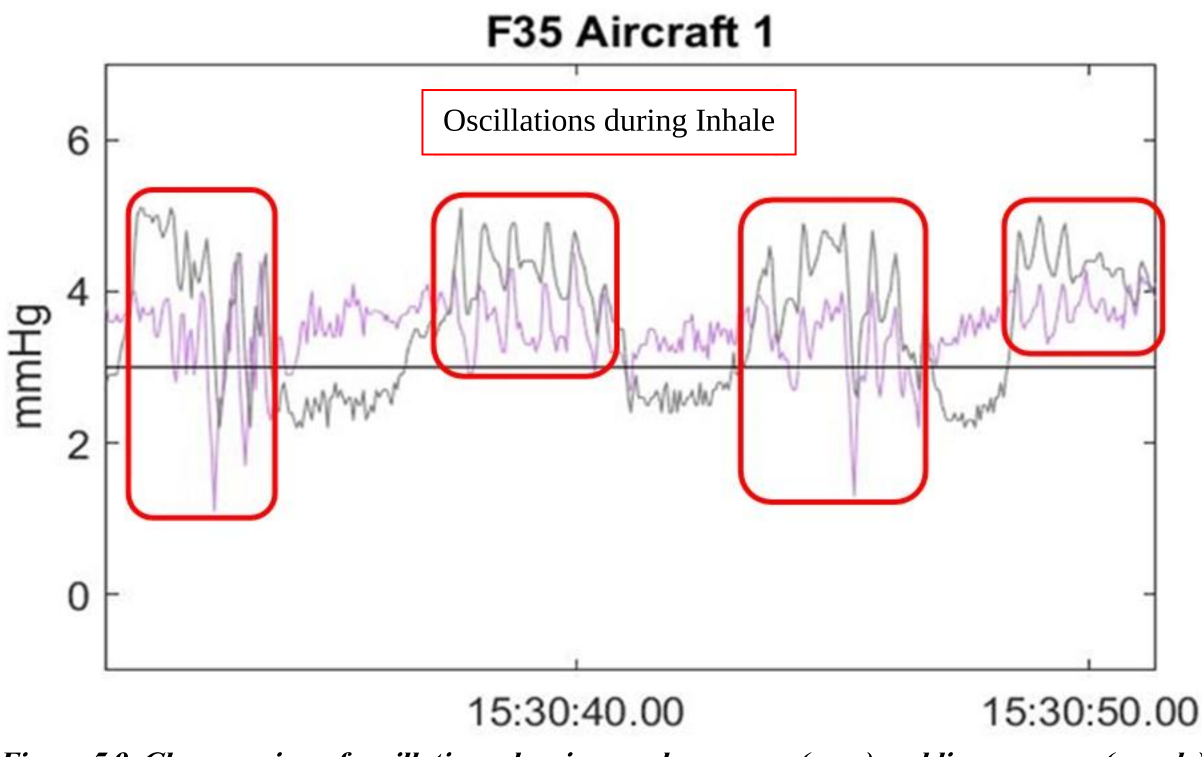


Figure 5.9. Close up view of oscillations showing mask pressure (grey) and line pressure (purple) on Aircraft 1.

Note that the data comes from two physically separate sources; the mask pressure from the ESB and the line pressure from the ISB. The use of the ESB and ISB signals in correlation with each other is supported by over 100 PBA flights, and is an example of the redundancy and error checking available with the multiple overlapping redundant sensors. This data are further supported by pilot interviews on the difficulty of exhalation, as well as reports of being cut-off mid-sentence by increased exhalation pressure.

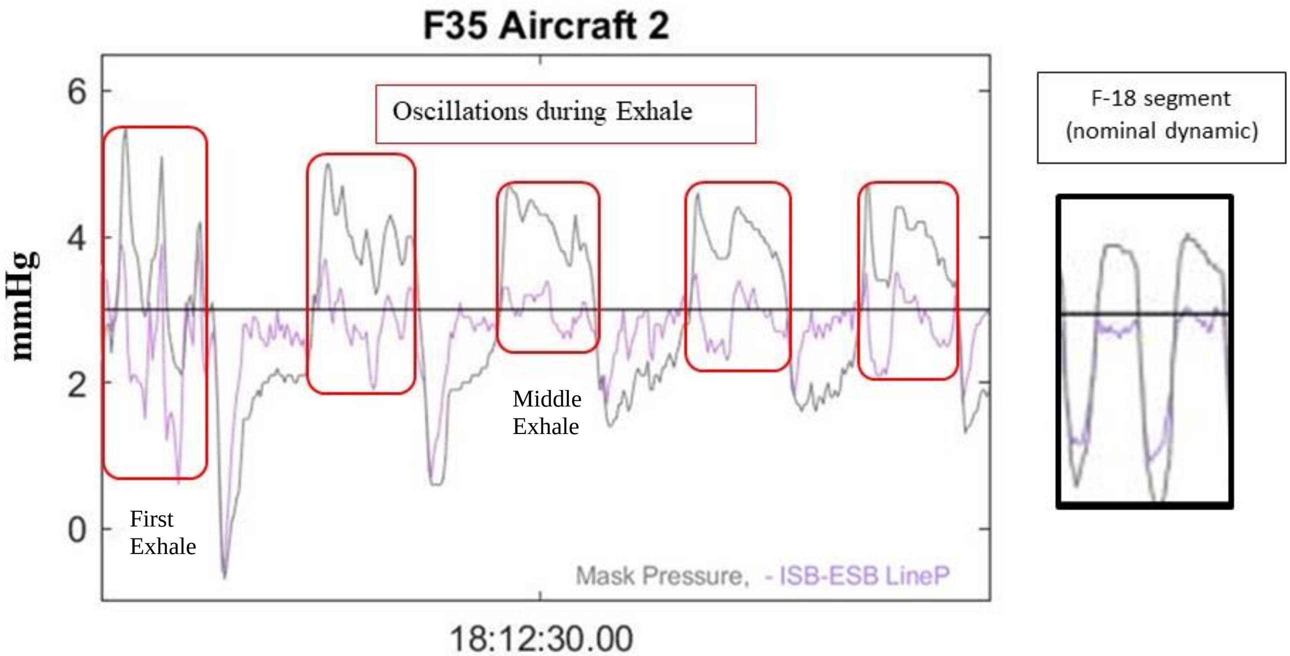


Figure 5.10. Close up view of oscillations showing mask pressure (grey) and line pressure (purple) on Aircraft 2.

The exhale oscillations on Aircraft 2 while less frequent, are still pervasive. The middle exhalation in Figure 5.10 is the closest to a normal exhale with line pressure staying close to safety pressure, minimal oscillations, and only one drop of less than 1 mmHg. However, the first exhale has very sharp swings approaching 3 mmHg. Generally, Aircraft 1 has larger oscillations during exhalation and Aircraft 2 has larger oscillations during inhalation. A small sample of the F-18 data from Figure 5.5 is shown at right for comparison.

5.4.1 Disrupted Pressure-flow Relationships during Exhale

Pressure-flow relationships during exhale are again so disjointed that they have no discernable functional relationship to each other. The first thing to notice after exhale starts at the red triangle (Figure 5.11) is that pressure increases with no flow. The point at which flow starts is called the cracking pressure, which in an ideal system would be at the nominal safety pressure of the regulator. Here we see cracking pressures on both jets ranging from 4 to 5 mmHg, which is much higher than the nominal safety pressure of 3 mmHg. Once flow begins, the traces are characterized by a decline in pressure. This is a backwards relationship. Flow initially starts at a higher cracking pressure than designed, and then gradually decreases until peak exhale flow is reached on every breath. After peak flow, pressure increases markedly (approximately 1 mmHg) accompanied by a decrease in flow. Again, this is an inverted relationship. Higher exhale pressure should result in more flow if the exhale resistance is constant. If the resistance is increasing, however, flow will be choked off and pressure will increase concordantly.

Unlike the inhale breath where the regulator is directly involved in the dynamics of flow, exhale flow is only a function of the exhale valve mechanics and pressure balances. The compensation bladder in the exhalation valve references the inhale line pressure, and is the mechanism which stops or restricts flow. Because the exhale compensation valve is connected to the line pressure, pressure oscillations in this line can cause variable flow restrictions during exhale, which can be observed happening in virtually every exhale.

The Exhale Breath Number 116 (EBN 116, Figure 5.11, top right) is notable as it has the most linear relationship during the second half of the exhale (denoted by the green line). An ideal exhale flow would track closer to the green line, which serves as a comparative reference to how far removed from linear these flows are.

Aircraft 1 has higher cracking pressures, larger flow restrictions, and more pressure fluctuations (compared to Aircraft 2; and together they have characteristics exceeding those found in F-18's during the PBA study. These observations corroborate pilot reports of increased backpressure sensation, and restriction to flow.

The flow patterns in Figure 5.11 are consistent with a restrictive exhalation pattern with breathing dynamics characterized by an unpredictable and variable pressure-flow relationship marked by excessive cracking pressure and intermittent flow restrictions. This combination can result in flow reductions of 15 to 20%. Remembering that the only mechanism the human body has to control breathing is pressure, an inverted or non-existent pressure-flow relationship like this will have physiologic consequences for the natural ability to properly control exhale volume. Additionally, an unpredictable and constantly changing average resistance, further complicates compensatory efforts.

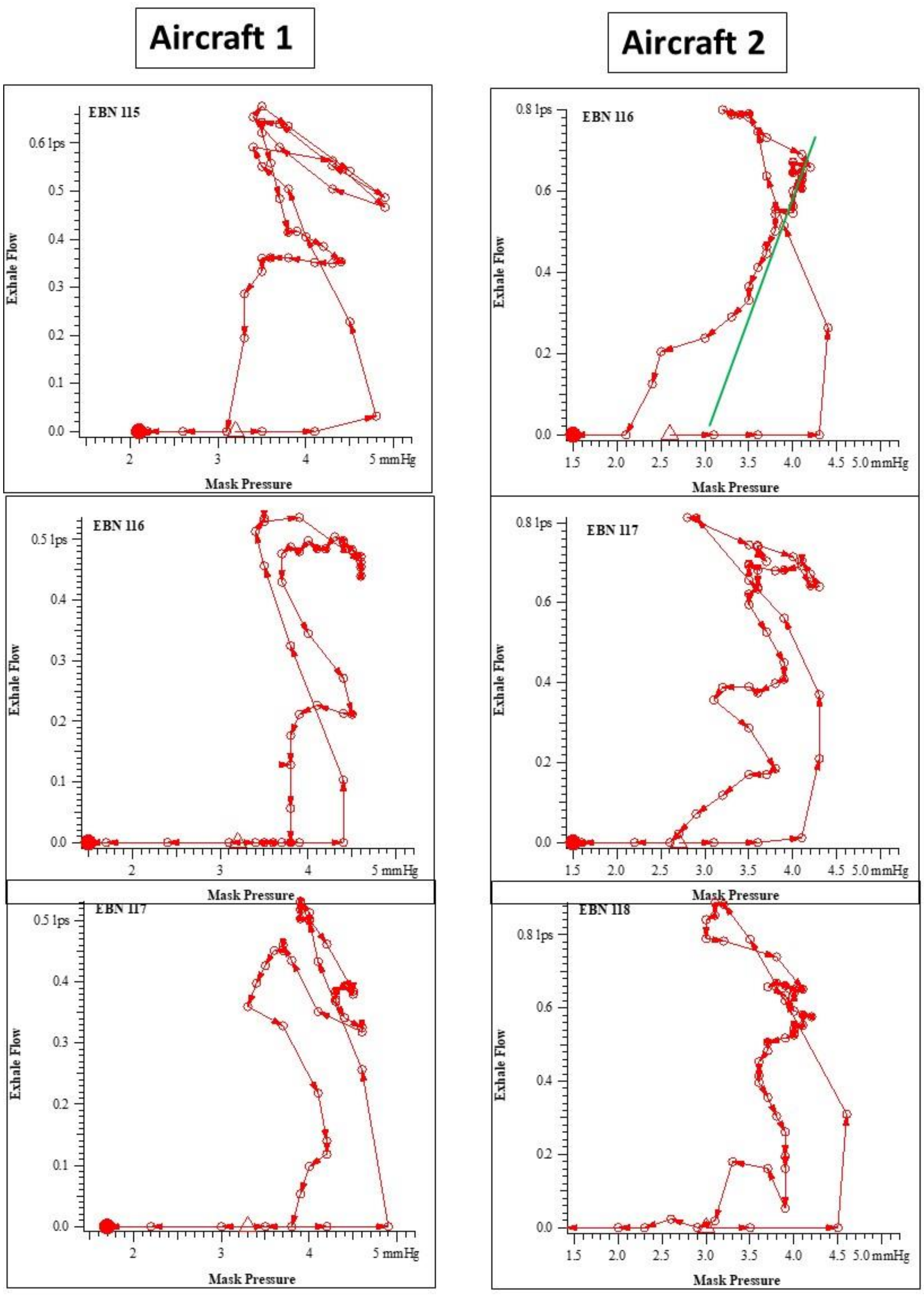


Figure 5.11. Exhale Flow versus Mask Pressure from Aircraft 1 and Aircraft 2.

5.5 Pressure Spikes and Pressure Drops: The F-35 Breathing System During Inhalation

The pressure spikes and oscillations present during inhale are circled in red in Figure 5.12. Both the mask pressure and the line pressure oscillate continuously at less than 0.5 mmHg. Aircraft 1 exhibits an unusual pattern with minimal pressure drop during inhale. These oscillations superimposed upon otherwise normal breathing (Figure 5.12) are of the same magnitude as pressures generated during normal breathing.

During inhale, the exhale valve should close, the inhale valve should open, and pressure in the mask should track closely with the line pressure. During PBA flights in the F-18 (Figure 5.12, bottom) this concurrent drop in both line and mask pressure can be seen clearly. Notice that the line and mask pressures rise and fall together smoothly, indicating that the aircraft is breathing "with" the pilot. The strong (normalized) correlation (R=0.9) on PBA flights between mask pressure and resultant flow is discussed below and also shown in Figure 5.14 and 5.17. The mask pressure is essentially the demand signal from the pilot, while the line pressure is essentially the demand signal seen by the regulator.

Inhale line pressure on F-35 Aircraft 1, however, stays at safety pressure the entire time. Line pressure drops to its lowest, not during inhalation, but during exhalation due to oscillations! The line pressure and mask pressure show a major disconnect and frequently trend in opposite directions; this is a profound disconnect between pilot and machine. We have already seen that the correlation between mask pressure and flow was very low at R=0.42 for Aircraft 1 (Figure 5.16). Here we see that the correlation between mask pressure (the demand signal closest to the pilot) and the line pressure (the demand signal closest to the regulator) is very low or anti-correlated. Looking at breathing dynamics, a pilot's breathing should be supported by the aircraft according to the following pattern:

1. Both line pressure and mask pressure start at the same point, or with a fixed offset in the case of safety pressure.
2. The pilot inhales, the pilot's chest wall expands causing a pressure drop in the lungs.
3. The mask pressure begins to drop to follow the pressure drop in the pilot's lungs.
4. The mask pressure drop is communicated down the line by the regulator.
5. The regulator increases feed flow to the pilot until the inhale flow peaks.
6. The pilot's chest wall is harder to expand and lung pressure becomes less negative.
7. The mask pressure rises to follow pressure rise in the pilot's lungs.
8. The mask pressure rise is communicated to the line by the regulator, the regulator reduces flow until they match again at (1)

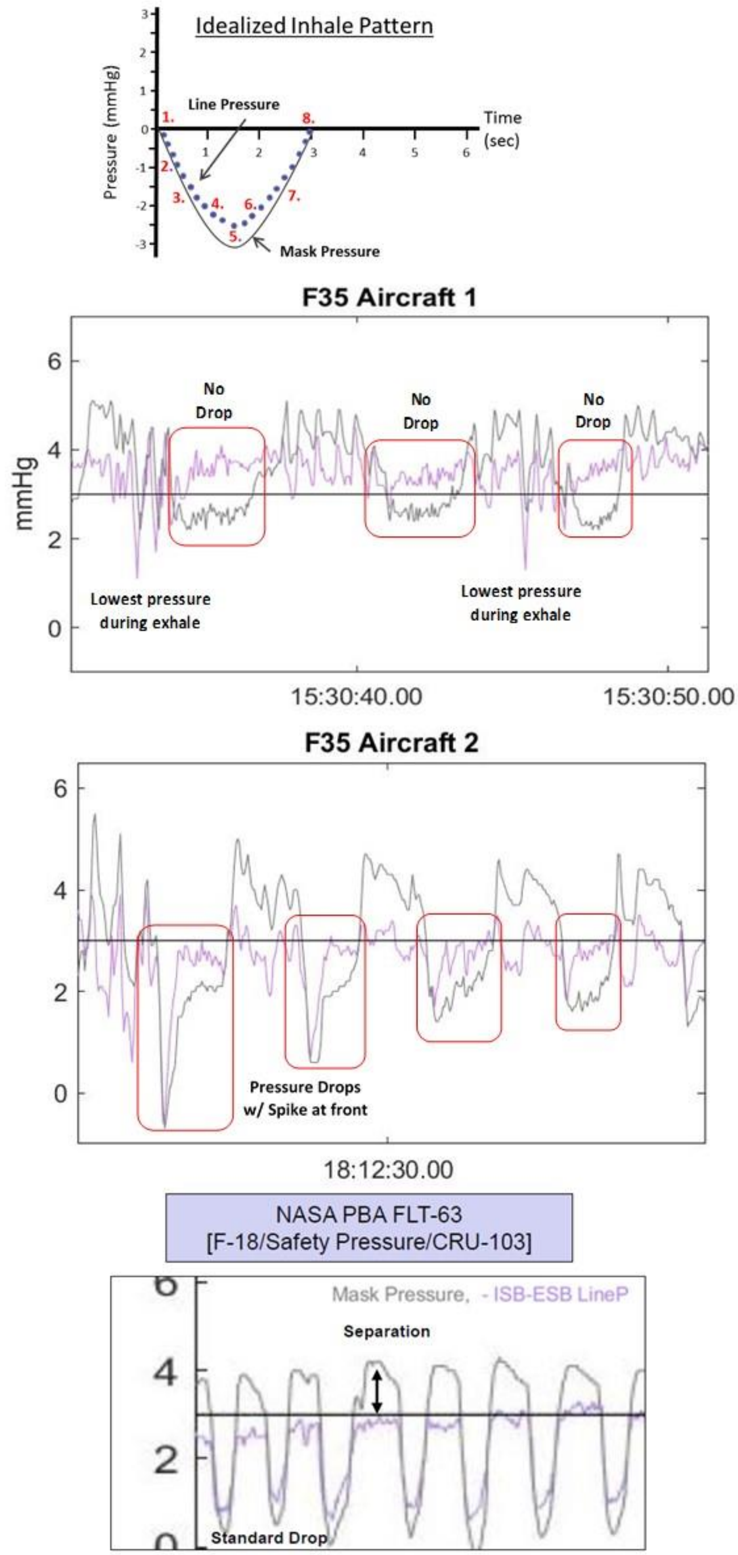


Figure 5.12. Mask Pressure vs Line Pressure Close up of inhale oscillations for F-35 Aircraft compared with nominal performance experienced in F-18.

The F-35 regulator has been compared to a racehorse, a very powerful thoroughbred, because it can send the air racing to the pilot. The energy necessary to overcome the pressure drops in modern fighter systems necessitates a strong regulator that can respond very quickly. Indeed, the F-35 has a very powerful regulator that responds quickly. This is necessary, however, when a finely tuned system capable of fast and large pressures is out of sequence or out of harmony with the pilot's demands, the same increased power and speed have an equally increased ability to cause disruption.

5.6 Phase Shift: A Metric to Characterize Pressure-Flow Disharmony

Is there a simple way to characterize significant pressure-flow disharmony? Nearly 100 PBA flights show that overlaying Mask Pressure and Flow Rate squared is a sensitive indicator of anomalies. The analysis of resulting anomalies suggested a simple way to characterize disagreements between pressure and flow by comparing the respective pressure-flow peaks. In order to define disharmony, the nominal pressure-flow relationship must be defined first.

Ideal Pressure-Flow Relationship: Flow is resultant as pressure changes at one point of a system compared to another. The relationship between flow and pressure is defined by the nature of the flow, which can be laminar (streamlined), transitional, or turbulent, and is characterized by the Reynolds number (Re).

Reynolds Numbers for the Tracheo-Bronchial Tree

Location	Diameter mm	Velocity 6 L/min	Velocity 60 L/min	Velocity 200 L/min
Nasal canal	5	400	4,000	12,000
Pharynx	12	800	8,000	24,000
Glottis	8	1,600	16,000	48,000
Trachea	21	1,250	12,500	37,000
Bronchi	17	910	9,100	27,300
Bronchi	9	700	7,000	21,000
Bronchi	6	570	5,700	17,100
Bronchi	4	190	1,900	5,700
Bronchi	1	35	350	1,050

Figure 5.13. Normal Reynolds Numbers for the Tracheo-Bronchial Tree (Physiological Reviews 41:314, 1961).

Turbulent flow transitions when Re > 2000. Reynold's number increases with the increase in linear velocity of gas (flow rate), density of gas, or radius of tube. As an example, breathing in quickly (which occurs during G-breathing) creates more turbulent flow throughout the tracheobronchial tree and significantly increases the work of breathing. From Figure 5.13, in the Nasal Canal, flow starts to become turbulent at flow rates greater than 30 L/min. Pilot air supply flow rates measured with instruments such as VigilOX (at altitudes under 23 kft) are lower-bound at 40 to 50 LPM, with flow arriving via tubes with radius larger than in the human system, thus the supply flow is above the Reynold's number for turbulent flow at peak flows.

$$Q = k\sqrt{\frac{P_1 - P_2}{\rho}}$$

For pilot breathing, the square of Q (supplied turbulent flow) is approximately proportional to the differential pressure ΔP. While not an exact solution to the pressure-flow relationship due to transitional flow dynamics, this relationship is useful and documented during the more than 100 flights analyzed by the PBA on specially instrumented F-18 LOX supplied aircraft.

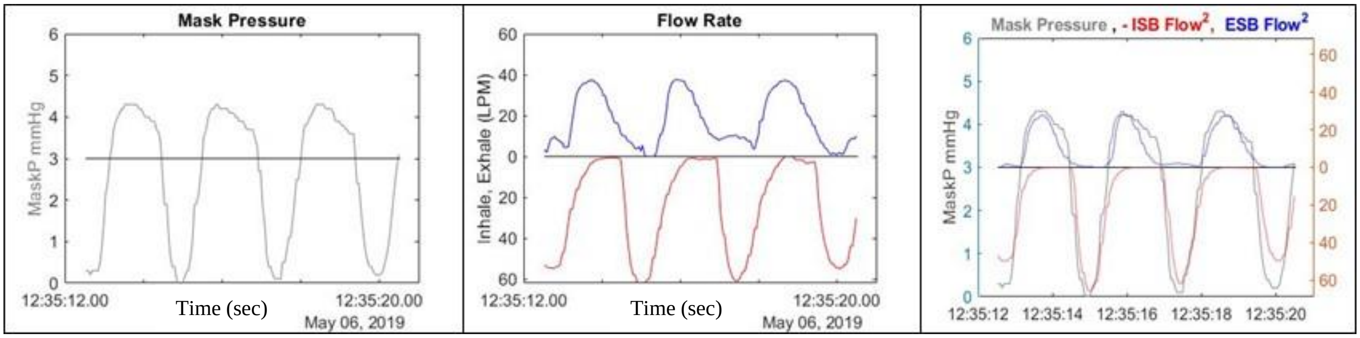


Figure 5.14. Mask Pressure (left), resulting Flow Rate (middle), and correlation when superimposed (right), shown using an F-18 sample. This is in direct conflict with observed F-35 behavior.

As shown in Figure 5.14, when mask pressure is superimposed with flow squared, it yields a strong correlation. We note that the rising edge of the flow is preceded by the mask pressure signal by 1 sample time (1/20th second). The smooth pressure contour is a stark contrast in comparison to the jagged contour of the F-35 mask pressure

Pressure-Flow Disharmony is a mismatch between the pressure profile and the flow profile, including start/stop and time it takes to reach the peak (maximum). In the example (Figure 5.15), a **mismatch** between the Grey Mask Pressure and the Blue ESB (Exhalation) Flow^2 is shown (in the red box).

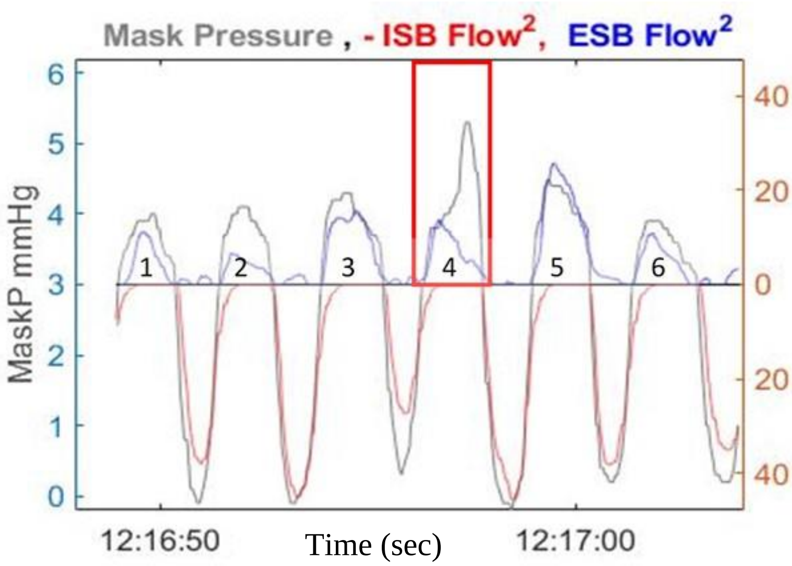


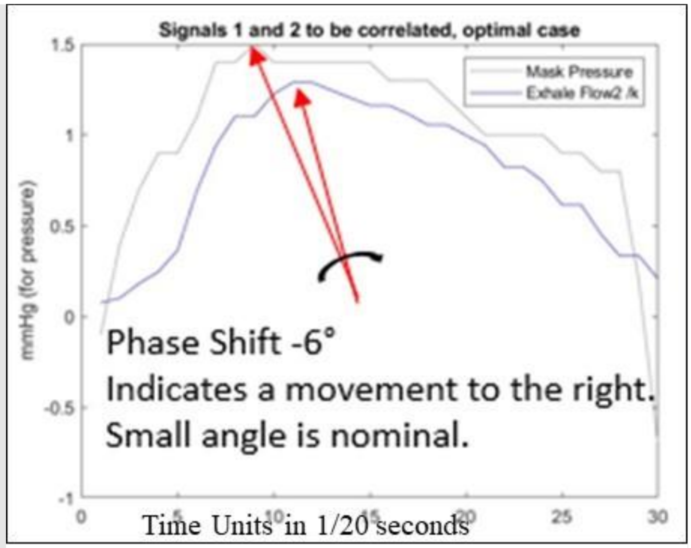
Figure 5.15. Exhale Breath #4 flow peaks at start of exhale. Mask pressure peaks at the end, as flow trends down. Shown using an F-18 sample. Breath #4 is an infrequently anomaly.

Ideally, exhalation flow is an instantaneous response to a pressure signal. During exhalation through a mask, flow is expected to lag slightly behind pressure due to exhalation valve cracking-pressure and finite valve resistance. For real life examples we enlarge exhale breaths #4 and #5 from Figure 5.15.

Negative phase shifts indicate that mask pressure peaks before the flow peaks (Figure 8.15 top).

The smaller the lag, the more ideal the system (small negative numbers are expected).

The larger the lag, the more resistance in the system (e.g. when a valve that is sticky or "Slow to Open", the pressure builds up, the valve opens with a delay, then flow peaks).



Positive phase shifts indicate that flow peaks before mask pressure peaks (Figure 8.16, bottom).

This can happen when the exhalation flow is pinched off after exhale flow starts. Flow decreases and pressure increases.

Imagine a valve that closes too early, pinching off flow (e.g. due to safety pressure in the compensation valve as seen in Figure 8.11 repeatedly)

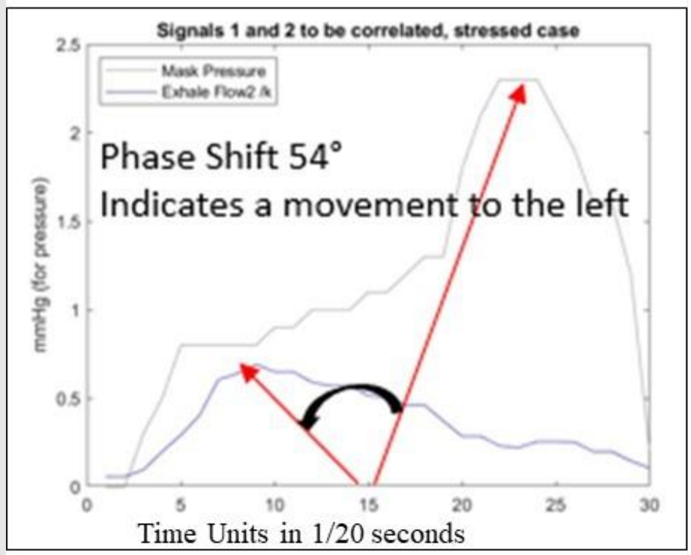


Figure 5.16. Exhale Breath #5 (top) and Exhale Breath #4(bottom) zoomed in view of breaths from Figure 5.15, shown using an F-18 sample.

Phase Shift in degrees builds on finding the optimal time-shift between 2 signals and takes in consideration the length of the exhale. Since breath time varies every breath, we can normalize each breath by its length such that the breath phase length totals 180 degrees. The red arrows (Figure 5.16) point to the peak flow and peak mask pressure, and between themselves, have a corresponding phase angle between 0 to 180 degrees. 20Hz sample times mean that if the peaks are off by one sample, there will be a phase shift of around 6 degrees (depending on the breath time).

Both of these sensations are experienced regularly in mask breathing, and pilots adjust to small phase shifts routinely.

<u>Quantitative Results</u>: Inhalation was analyzed in the same manner as exhalation, and distribution plots prepared for comparison. These histograms show the distribution of phase shifts present on the F-18 and F-35 for comparison. Dozens of PBA flights were characterized regarding phase shift. F-35 data was limited to the 2 tests described in this report.

For the F-18, Figure 5.17 (top 4 plots) shows how well pressure and flow match, with minimal delay on inhale (minimal negative phase shift). It may be helpful to think of negative phase shift as a valve that is "Slow to open". During exhale, there is no positive phase shift, no pressure build-up in the mask, and minimal lag (minimal negative phase shift).

For the F-35, Figure 5.17 (bottom 4 plots) shows far greater ratios of negative phase shifts compared to the F-18s and major mismatches in pressure/flow during both inhale and exhale. Both F-35 also have far greater ratios of positive phase shifts during exhale. It may be helpful to think of positive phase shift as a valve that is "Early to close". Positive phase shift only occurs on exhale with few exceptions.

On Aircraft 1, the mode of Phase Shift is skewed to the left -30 degrees (in contrast to 0 degrees for other jets evaluated), with a wide distribution of phase shifts to the left and right. This graphically illustrates the preponderance and magnitude of the pressure-flow mismatches at a glance. While pressure-flow mismatches can be seen clearly in other data products showing select breaths, this metric is powerful because it creates a view of the pressure-flow characteristics over the entire data set in order to see systemic effects. Aircraft 1 has a quantifiable delay during inhale where the flow lags the pressure demand by 30 degrees on average, and very few breaths with 0 degrees phase shift. In comparison, Aircraft 2, the "normal breather," had approximately half of the inhales with 0 degrees phase shift. This is an indication of a systematic inhale flow restriction and a perfect example of a pervasive breathing sequence disruption or disharmony.

<u>Correlation Results</u>: Normalized Correlation (R) compares paired points of the signals. This method can be used to characterize how the shape of the pressure and flow of the entire exhale compare, not just the timing of the peaks as is done with phase shift. The output is between 0 and 1. A value greater than 0.9 is a high correlation. Values for R in the F-18 are found to be around .9, as the teaching example from Figure 5.5 graphically showed earlier with pressure and flow closely matching the entire time. Values for R of 0.5 indicate a very large mismatch in correlation.

Correlation numbers are 0.42 to 0.59 for the F-35 aircraft over the course of 20 minutes on the ground only, contrasted with 0.9 for the 1-hour flights on the F-18 aircraft. Correlation indicates the magnitude of the overall match or mismatch of pressure with flow, whereas phase shift provides insight into the direction and source of the mismatch in pressure and flow. These low correlations numbers are in agreement with, and a good quantitate measure of the visual hysteresis shown in the breath-by-breath examples of Figure 5.3.

Phase shift and correlation results are in agreement with the breath-by-breath hysteresis plots and are a useful quantitate measure of the breathing sequence disorder that is visually apparent on plots of individual breaths. From the above phase shift analysis and side-by-side analysis of the F-35 pilot breathing, it appears that the inhalation positive pressure scale and timing is over-compensating for lag (pressure-flow response time) in the system. Lag during inhale can result in reduced inhale flow and lag at the end of inhale can result in reduced exhale flow.

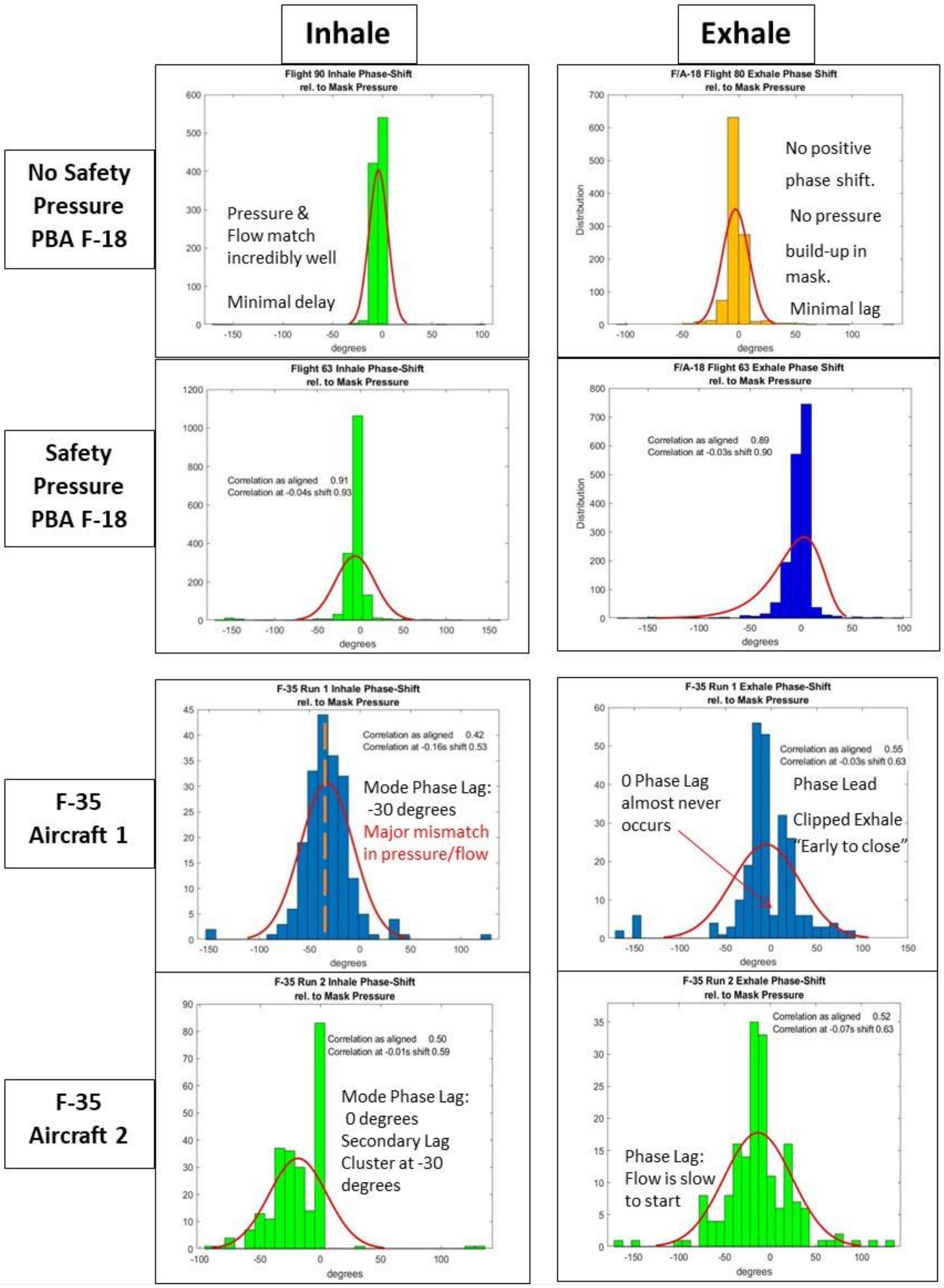


Figure 5.17. Phase Shift Plots of Inhale/Exhale for PBA F-18 and F-35 Aircraft 1 and 2.
F-35 aircraft exhibit increased phase shift and more erratic breathing behavior than legacy F-18 aircraft with or without safety pressure. In ideal breathing all flow should correlate to the driving pressure, and all instances should be in the (-10, 0] bin, even if we consider the slight delay breathing through a system.

A micro look at the F-35 Inhale: The demand safety pressure regulator system in the F-35 is aggressive at maintaining/restoring a high safety pressure. Peak Inspiratory Pressure (i.e., the peak drop in pressure, since inspiration decreases pressure) (Figure 5.18, top) is predominantly at the very beginning of the breath where the pressure drop from an inhaled breath is steepest. This can also be seen in Figure 5.3 where pressure drops, but there is no flow. This explains why inhale phase shift is almost always negative. Also, the Peak Inspiratory Flow (Figure 5.18 bottom) has jagged pressure plateaus due to inspiratory pressure oscillation. This is the source of the large variation in distribution of the phase shift; flow reaches its peak in a chaotic fashion, but always late. Whether the timing and pressure response of the F-35 regulator is designed this way intentionally is unknown: the regulator is a black box.

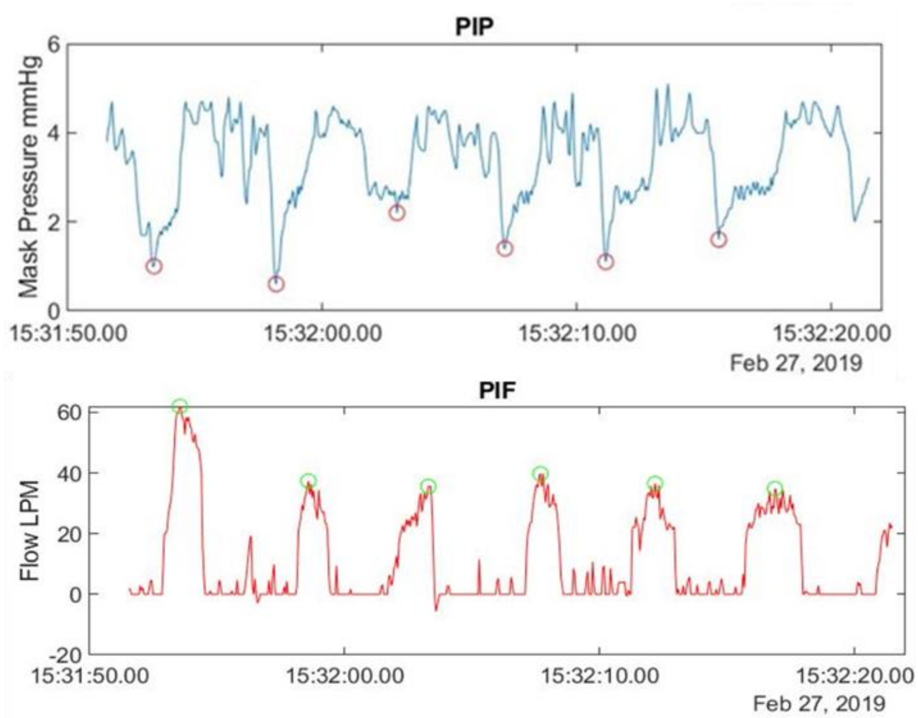


Figure 5.18. Sample F-35 Peak Inspiratory Pressure (PIP) and Peak Inspiratory Flow (PIF), where the flow should be much closer co-aligned as a response to the driving pressure

Phase Shift Analysis is a numerical tool to quantify disharmony between pilot breathing pressure and the breathing system flow (pilot demand vs. aircraft supply). The test results on the F-35 are corroborated by independent pilot observations. The F-35 presents quantifiable phase shift disharmony during inhale and exhale through its breathing system. The values of these shifts indicate significant deviations from the ideal pressure-flow relationship, and are much greater than in the F-18. Phase shift analysis addresses specific causes and outcomes, but does not address the entire breadth of the issues at work.

For flights where both mask pressure and flow are available, apply phase shift and hysteresis analysis for early detection of equipment issues, or validation of pilot reports. Flights or segments can be collapsed into single numbers of Phase Shift Mean, Standard Deviation, Lag time, and correlation coefficients.

5.7 Energy Management: Pressure Oscillation FFT and Dynamic Pressure

Pressure oscillations, like all waves, carry energy. After taking the Fast Fourier Transform (FFT) of the mask pressure signal to analyze the frequency in comparison to the F-18 (Figure 5.19), a concerning observation emerges. Between 2 to 6Hz there is an order of magnitude more frequency content in F-35 Aircraft 1 compared to the F-18. Power is the coefficient of the FFT squared. So a factor of 10 in the coefficient is a factor of 100 in the power. That could be a lot of energy the pilot basically has to absorb or fight. These oscillations are not present on PBA flights and in the F-35 these oscillations exceed the AIR-STD 4039 as discussed in Section 6.

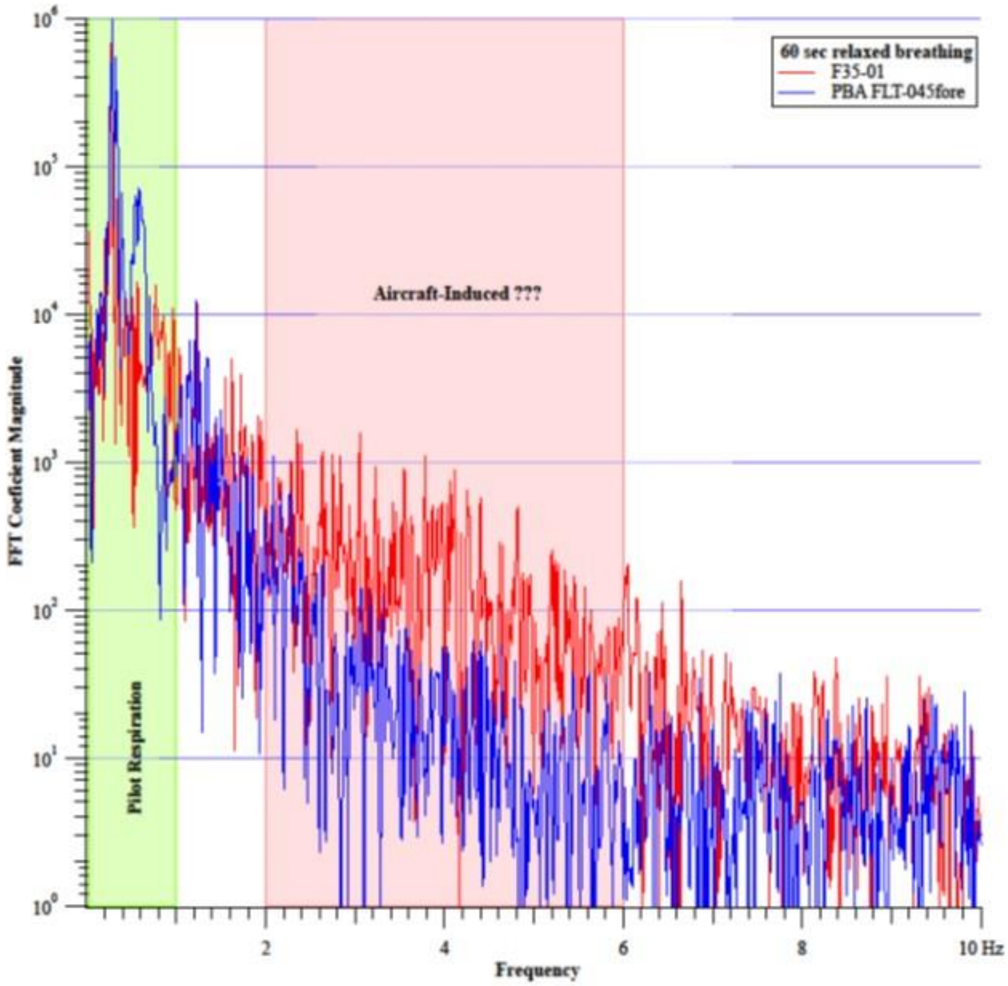


Figure 5.19. Fast Fourier Transform comparing F-18 to F-35 mask pressure frequency components demonstrating the increased power loading on the pilot breathing response in F-35.

This is a single comparative data point and should be viewed accordingly. What is clear is that the F-35 exceeds the standards for allowable pressure oscillations and exhibits a profound disconnect in its attempts to quickly and forcefully respond.

5.8 Perception of Breathing Dynamics

Exhalation is difficult in the F-35. Mask pressure swings resembling a saw tooth during exhalation (in contrast to a smooth peak or a steady plateau) are characteristic of the chaotically changing pressure conditions inside the mask due to sources other than the pilot. Constantly changing mask pressures during exhalation predominantly track the changes of inhale supply line pressure, which should not be changing.

Pilot feedback, observations of the raw data, and processing of the data as in the frequency curves (Figure 5.19) all agree. Excessive exhale pressure is a common complaint in pilot feedback, the raw data exhibit extensive pressure fluctuations equal to or greater than pressures used during normal exhale, and the hysteresis plots demonstrate disruptive dynamics consistent with mid-speech pressure kickbacks that can stop vocalization.

The transition between inhalation and the start of exhalation is inconsistent. Sometimes F-35 breathing transitions are smooth and seamless; sometimes there is a staggered transition between the end of inhalation and the start of exhalation. Breathing challenges during inhalation and exhalation routinely come to the pilot's conscious attention and exceed the ability of human physiology to compensate without conscious effort.

6.0 System of Systems Interaction

It has been previously stated by the NESC that aircraft act as a "System of Systems". That is, the aircraft is a conglomerate of individual systems, with small changes in the behavior of any one system potentially contributing to an aggregate effect which may lead to large impacts on the aircraft as a whole. This effect was widely discussed in the previous 2017 report by the NESC F-18 PEAT. The F-35 exhibits "system of systems" behaviors.

The F-35 data shown in Figure 2.1 were the main input to the design of this test. The changes in breathing dynamics with the selection of defog and removal of the G-suit were so remarkable and noticeable that it drove the design of experiment selected. At the time, little was known about the F-35 breathing dynamics, so large repeatable changes were targeted on systems known to cause noticeable changes for comparative analysis. The selected points were not conditions an operational pilot would be expected to encounter for extended periods of time under normal circumstances. They were intended to elicit the underlying dynamics responsible for the subjective exhale backpressure which has been extensively documented. The points listed below are selected the full data set of script points (Tables 7.1 and 7.2).

First, however, breathing standard requirements are shown for understanding of how the F-35 data compares to established standards:

Military Standard 3050 / Air Standard ACS (ASMG) 4039	[Figure 6.1]
Trumpet Curve Plots / Mask Pressure Swing Plots / Oscillatory Activity	[Figure 6.2]
System of System Comparisons:	
Normal Relaxed Breathing (Baseline Breathing)	[Figure 6.3]
Effects of Maximum Inhale (2x Max Inhale/Relaxed Exhale)	[Figure 6.4]
Effects of Backup Oxygen System (100% Oxygen)	[Figure 6.5]
Effects of Defog On (Defog Full On – Hi Flow/Hi Temp)	[Figure 6.6]
Effects of G-Suit Interaction	[Figure 6.7]
Push-to-Test (PTT), G-suit Connection, and Mask Off/On	[Figure 6.8]

Effects of Maximum Inhale (without G-suit)	[Figure 6.9]
Effects of Rapid, Deep Breaths (without G-suit)	[Figure 6.10]
Effects of Increased Engine Power Setting (without G-suit)	[Figure 6.11]

6.1 Standards Review

Military Standard 3050

Trumpet curves are one of the traditional tools for of analyzing a regulator's performance during peak inspiratory and expiratory flows in order to ensure that mask pressure does not become excessive. The specifications of these curves are detailed in MIL-STD 3050 (Figure 6.1, top). The values for aircraft with safety pressure are different than for aircraft without safety pressure, and the values applicable to the F-35 are circled in red. Note that in addition to the minimum and maximum mask cavity pressure for each given flow value, there is also a maximum swing value. These values are plotted for Segment 1 (Figure 6.1, top and middle).

Air Standard ACS (ASMG) 4039

The standards for oscillations are detailed in AIR STD ACS (ASMG) 4039 (Figure 6.1, bottom). The general requirement is straightforward: Not produce significant oscillations of pressure within the mask cavity. Note that this requirement applies to the "complete breathing system", but is measured at the nose and mouth of the user, termed the 'mask cavity'. The detailed requirement for what is termed 'Oscillatory Activity' is circled in red, prohibiting any oscillations lasting longer than .25sec from exceeding a double amplitude (peak to peak) pressure of .25inWG (or .25 in H2O). These values are plotted for Segment 15 on Aircraft 1 and Segment 1 on Aircraft 2 respectively (Figure 6.2, bottom). It has been noted that the curves have not been evaluated or corrected for any potential influence (added resistance) of adding the VigilOX ISB and ESB into the breathing loop; these effects are believed to be small.

Applicability to the F-35

The F-35 program represents one of the largest military acquisition programs in history and discussion of the process for accepting risk, notably the decision to forego dedicated developmental testing of the breathing system, is well outside the scope of this paper. However, we note that while the standards shown in Figure 6.1 significantly predate this acquisition, the F-35 aircraft were not required to meet these standards.

TABLE I. Inspiratory and expiratory mask pressures.

Peak Inspiratory and Expiratory Flows (liter ATPD/min)	Mask Cavity Pressure (in Wg)		
	Limits to		
	Minimum	Maximum	Maximum Swing
	Without Safety Pressure		
30*	-1.5	+1.5	2.0
90*	-2.2	+2.6	3.4
150*	-4.5	+4.0	7.0
200^	-7.6	+6.0	12.0
258#	-7.6	+6.0	12.0
	With Safety Pressure		
30*	+0.1	+3.0	2.0
90*	-0.8	+3.8	3.4
150*	-3.5	+5.0	7.0
200^	-7.0	+6.6	12.0
258#	-7.0	+6.6	12.0

* Cabin altitude from Sea Level to 38,000 feet.

^ Cabin altitude from Sea Level to 7,999 feet.

Cabin altitude from 8,000 feet to 38,000 feet.

AIR STANDARD ACS (ASMG) 4039

Minimum Physiological Requirements for Aircrew Demand Breathing Systems

2. General Requirements. Breathing systems for aircrew shall:

h. Not produce significant oscillations of pressure within the mask cavity.

3. Detailed Physiological Requirements. The performance of breathing systems for aircrew shall meet the following physiological requirements. In order to ensure that these requirements apply to the complete breathing system the performance is specified at the entry to the nose and mouth of the user. This site is termed the 'mask cavity' in this Air Standard.

f. Oscillatory Activity. The double amplitude of any oscillation of pressure in the mask cavity and which lasts 0.25 sec or longer shall not exceed 0.06 kPa (0.25 inch water gauge).

Figure 6.1. Chart excerpt from MIL-STD 3050 dated 11 May 2015 (top). Oscillator Activity excerpt from AIR STD ACS (ASMG) 4039 dated 12 Feb 1988 (bottom).

6.2 Comparison to Standards

Trumpet Curve Plots

The mask pressures for Aircraft 1's trumpet curve are all well within the limits. Note that both the inhale and exhale peaks are clustered below the 50 LPM (Figure 6.11, top left), as opposed to the more even distribution seen on Aircraft 2.

The mask pressures for Aircraft 2's trumpet curve are mostly within the limits with a few exceptions that are clustered around the lower limit during inhale (Figure 6.11, top right).

We acknowledge that the introduction of any measuring device adds a factor (in this case expected to be a minimal offset) to the phenomena being measured. It is not our intent characterize any offset here, but to focus on dynamics and differences between these data and those taken similarly in other PBA aircraft.

Mask Pressure Swing Plots

The mask pressure swings on Aircraft 1 are clustered between 30 to 50 LPM and below 1inH_2O (2 mmHg). These values are unusually low, and well within the specification. The cluster corresponds with the trumpet curve values clustering, and together with the pilot's report of feeling as if breathing was constrained, raise an unexpected issue. Mask pressure is typically thought of as a demand signal from the pilot because of the linear relationship between pressure and flow in the absence of a regulator. However, under conditions where pressure-flow relationships are non-linear, as was shown previously, that relationship breaks down. Here the low mask pressures appear to be a distinct indicator of a broken pressure-flow relationship, and not an indicator of reduced demand from the pilot.

The mask pressure swings on Aircraft 2 exceed the MIL-STD-3050 specification limit approximately 50% of the time. Note that the values plotted for the mask pressure swings are just peak values, not all data points. Hence, points are expected near the limit line. Ignoring the outliers, mask pressure swings routinely exceed 3 inH_2O. These are big pressure swings for such low flow. These pressure swings are concerning because they can contribute to several undesired physiological outcomes, not the least of which is barotrauma. These outcomes were unexpected. The mask pressure on the ESB and the flow sensor on the ISB are the two most trusted sensors. Both the data exceeding spec on Aircraft 2, and the unusually low values from Aircraft 1 should be cause for follow up investigation, especially given the difference dynamics between the two systems.

Oscillatory Activity

Exhale flow on the F-35 is characterized by extreme oscillations that exceed Air Standard ACS (ASMG) 4039 limits almost continuously. The magnitude of oscillations greatly exceeds the .25 inH20 limit on almost every single exhale. Several oscillations 5 times larger than the .25 limit can be seen (Figure 6.11, bottom). Segments in red exceed .25s from peak to trough on a single half-cycle swing. Most oscillations are about .2s peak to trough (2 to 3Hz), but continue to oscillate for much longer than .25 sec. This is extremely concerning due to the energy that can be contained in high frequency pressure oscillations in addition to any breathing sequence disruption. The potential harm from these exceedingly large and overwhelmingly pervasive out of spec pressure oscillations should not be discounted.

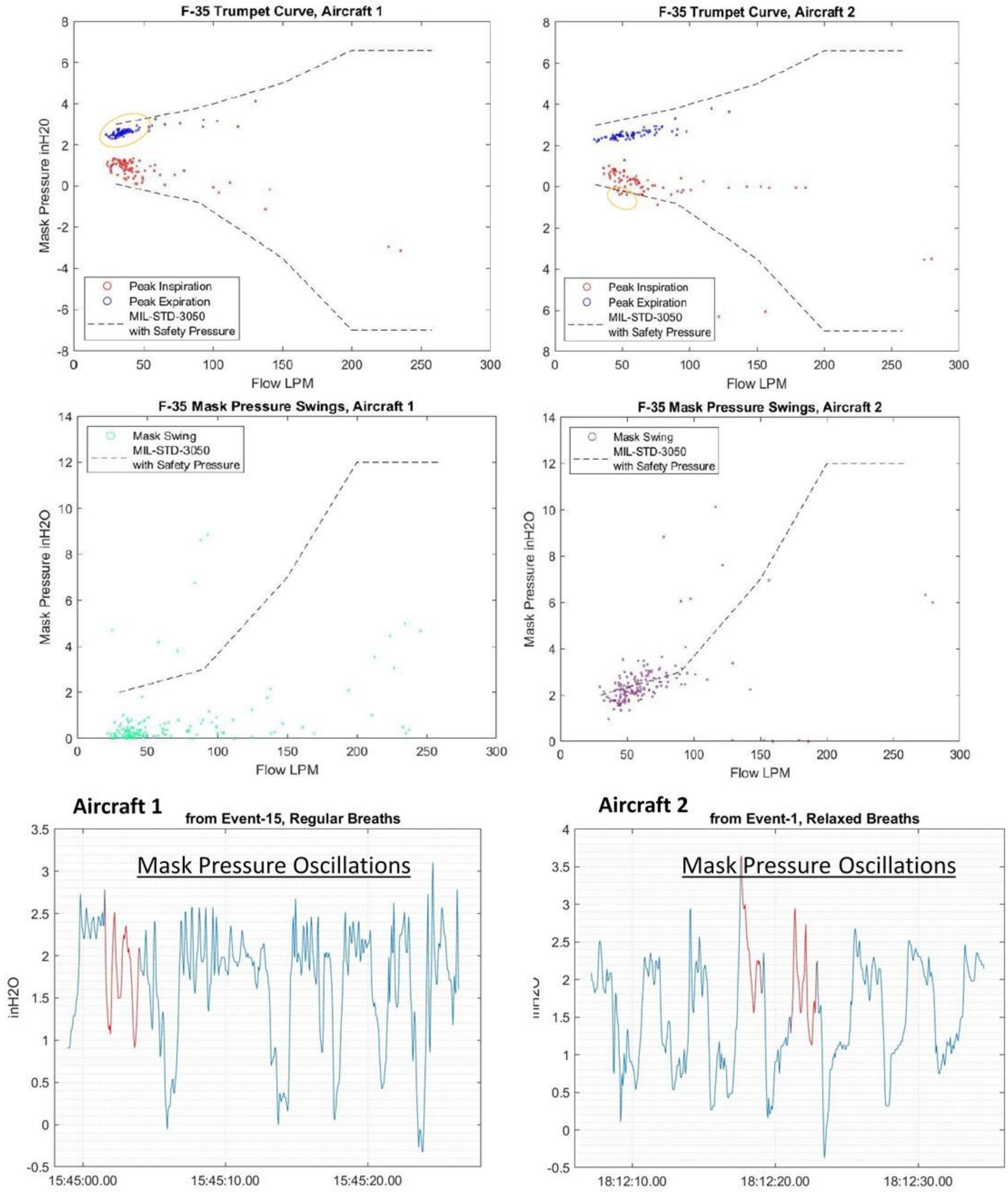


Figure 6.2. MIL-STD 3050 Trumpet Curves (top), MIL-STD 3050 Mask Pressure Swings (middle), Mask Pressure Oscillations (bottom).

6.3 Normal Relaxed Breathing

Prior to beginning the system level comparisons a few concepts must be defined. The following terms are discussed in more detail in the section on Physiology, but are defined here for reference since they are used extensively in this section.

Tidal Volume: The volume of air that is moved with each breath is defined as the Tidal Volume (TV). At rest TV is approximately 0.5 Liters or 500 mL, which can increase greatly with exertion. In this section, TV refers specifically to the volumes calculated from the ISB/ESB flows.

Minute Ventilation: Pulmonary ventilation is the volume of gas per unit time entering the lungs, often defined as Minute Ventilation (MV) in units of Liters/min abbreviated in this section as LPM. MV is a direct product of TV (liters/breath) and respiration rate (breaths/minute). MV requirements are driven by the body, as metabolic rates increase, MV will correspondingly increase to match the current physiologic needs. During a period of rest, and absent any acute changes in metabolic needs such as exertion, MV should demonstrate minimal variance over a short sampling period. Changes in MV observed within this data set are reflective of external forces on the human limiting physiological needs.

Inhale Flow (Red) and Exhale Flow (Blue) Conventions

Like the pressure versus time plots (Grey/Purple) that have already been introduced, the inhale/exhale flow versus time plots (Red/Blue) in Figure 6.1 are used extensively in this section. The convention for inhale flow is red, shown below the axis to line up with the pressure drops during inhale. The convention for exhale flow is blue, shown above the axis. The flow and pressure charts are time synchronized and shown one above another for easy comparison.

Normal Relaxed Breathing (Baseline Breathing)

Initial data was taken for resting, relaxed breathing in F-35 Aircraft 1 and 2 with no additional activities such as talking or body movement in the cockpit. This data are shown for Aircraft 1 and 2 in (Figure 6.3). TV and MV are significantly lower in Aircraft 1 than in Aircraft 2; with MV a full 50% lower, and TV 25% lower. The average mask pressure swing is lower on Aircraft 1 (the "bad breather") than Aircraft 2. Pilot interview stated that "The experience is one of breathing being constrained or limited". These lower mask pressure swings are indication of a flow limitation in the system, which would be interpreted by the pilot as restriction and limited air available to breathe. Breathing is inherently stochastic, and the reduction in variability on Aircraft 1 (the sinusoidal appearance of the flows with peaks all clustered near 30L/min) in comparison to the flows of Aircraft 2 (variable peak flows from 30 to 70L/min) is also an indication of a constraint.

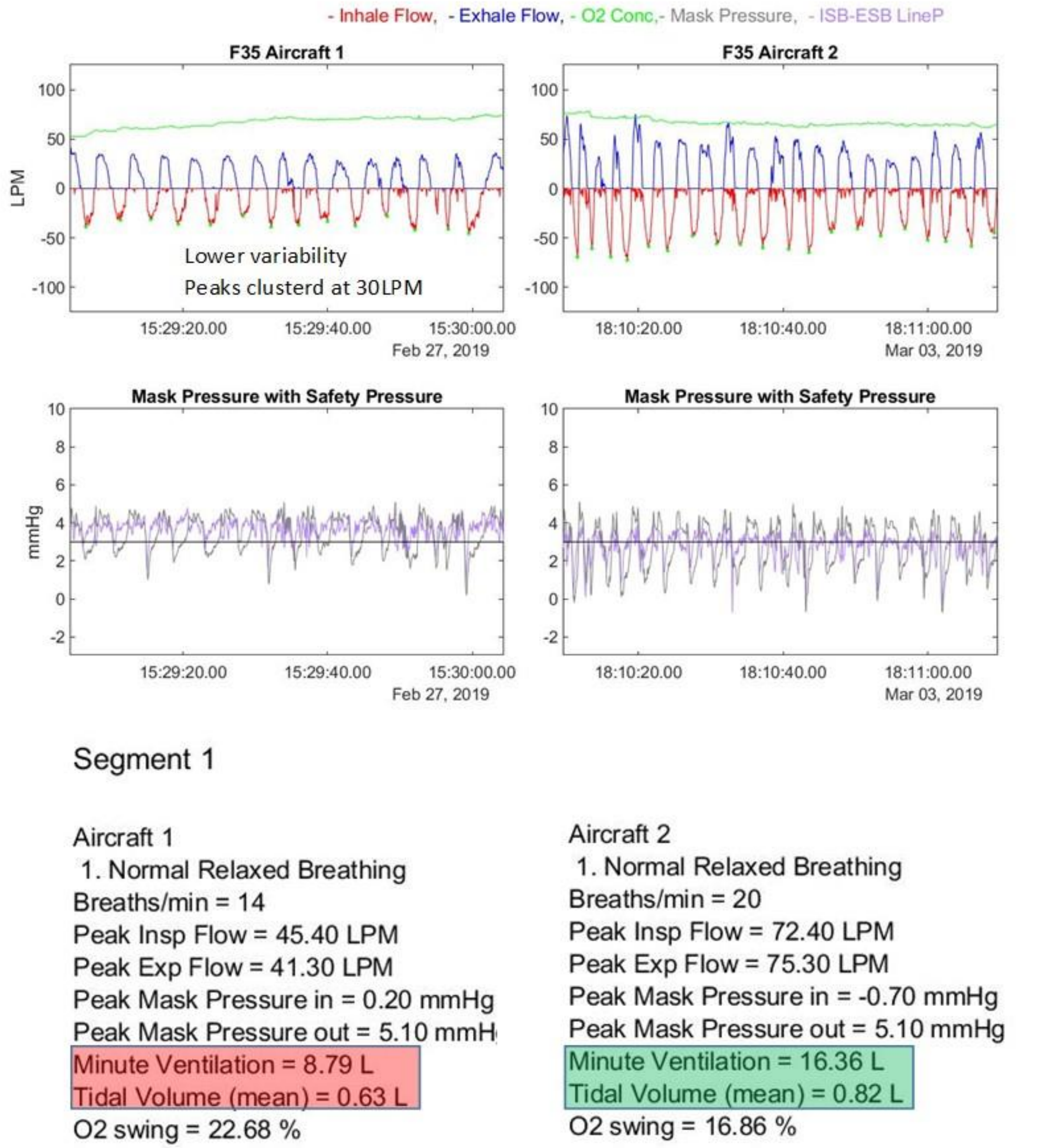


Figure 6.3. Baseline, Normal, Relaxed breathing for both F-35 aircraft during Segment 1.

6.4 Effects of Maximum Inhale

The positive pressure supplied by the F-35 system leads to unexpected dynamic behaviors when the pilot attempts a “maximum inhale”, or a sudden strong intake of breath followed by a relaxed exhale.

Maximum inhale maneuvers for the two F-35 aircraft allowed means of 3.4 L and 4.l0 L in single breath tidal volumes; although this represents a significant difference between the two aircraft, these numbers are not considered restrictive as the 99th percentile is 2.04 L for real-world flights from the main PBA study.

However, the breathing dynamics during exhale are characterized by a sharp exhalation shape and transitions from inhale to exhale that are not smooth (Figure 6.4). In Aircraft 1 there is significant lag as pressure increases during exhale before flow begins. Once flow begins, it rises rapidly to a sharp peak and then declines rather than maintaining a steady flow. Peak expiratory flow is higher at 117.9 LPM and occurs during the beginning of exhale due to the pressure build-up prior to flow occurring and the continuous decline throughout the remaining exhale. Breathing dynamics during inhale are characterized by a drop in line pressure that sharply reverses near 0 mmHg and returns to a nominal safety pressure during the remainder of the inhalation flow with overshoots of approximately 1 mmHg. The peak (negative) mask pressure is -6.5 mmHg, and the Peak Inspiratory flow is lower at 235.2 LPM.

In Aircraft 2, the breathing dynamics during exhale are characterized by a smoother transition from inhalation with a declining inhale flow rate that seamless transfers with no delay into an exhale flow rate that matches the rate (slope) of declining inhalation. The peak expiratory flow is slightly lower at 97.8 LPM due to the rounded distribution of flow over the duration of the exhale with the peak flow occurring near the middle of exhale. However, breathing dynamics during inhale are characterized by a line pressure oscillation of approximately 8 mmHg during both breaths. The peak negative mask pressure of -10.50 mmHg is more negative due to the oscillation; note that the peak negative mask pressure coincides with a 7 mmHg drop in line pressure, immediately followed by a rapid increase of 8 mmHg. The high frequency nature of these oscillations is not attributable to human input. Peak Inspiratory flow is higher for these two breaths at 279.6 LPM.

O_2 concentration is dropping for both aircraft (green line in the top graph of Figure 6.4) during the maximum inhalation test. While the aircraft is supporting the pilot’s increased breathing, instability of O_2 concentrations during maximum breathing are not desirable. Stability of O_2 concentration during maximum breathing is desired because decreases in O_2 concentration during increased breathing demand for O_2 are counterproductive.

While exhale was more impacted in Aircraft 1, inhale was more impacted in Aircraft 2. Notice that Aircraft 2, which was anecdotally described to be the “normal breather” aircraft, while exhibiting overall smoother exhale features, still has undesirable pressure fluctuations during exhale and more importantly demonstrates the largest line pressure oscillations seen in all of the data. Breathing dynamics depend on many different factors, and this exemplifies the importance of the testing all aspects of a system since the inhale/exhale dynamics can have problems both dependently and independently of each other and can vary from system to system (aircraft have personalities).

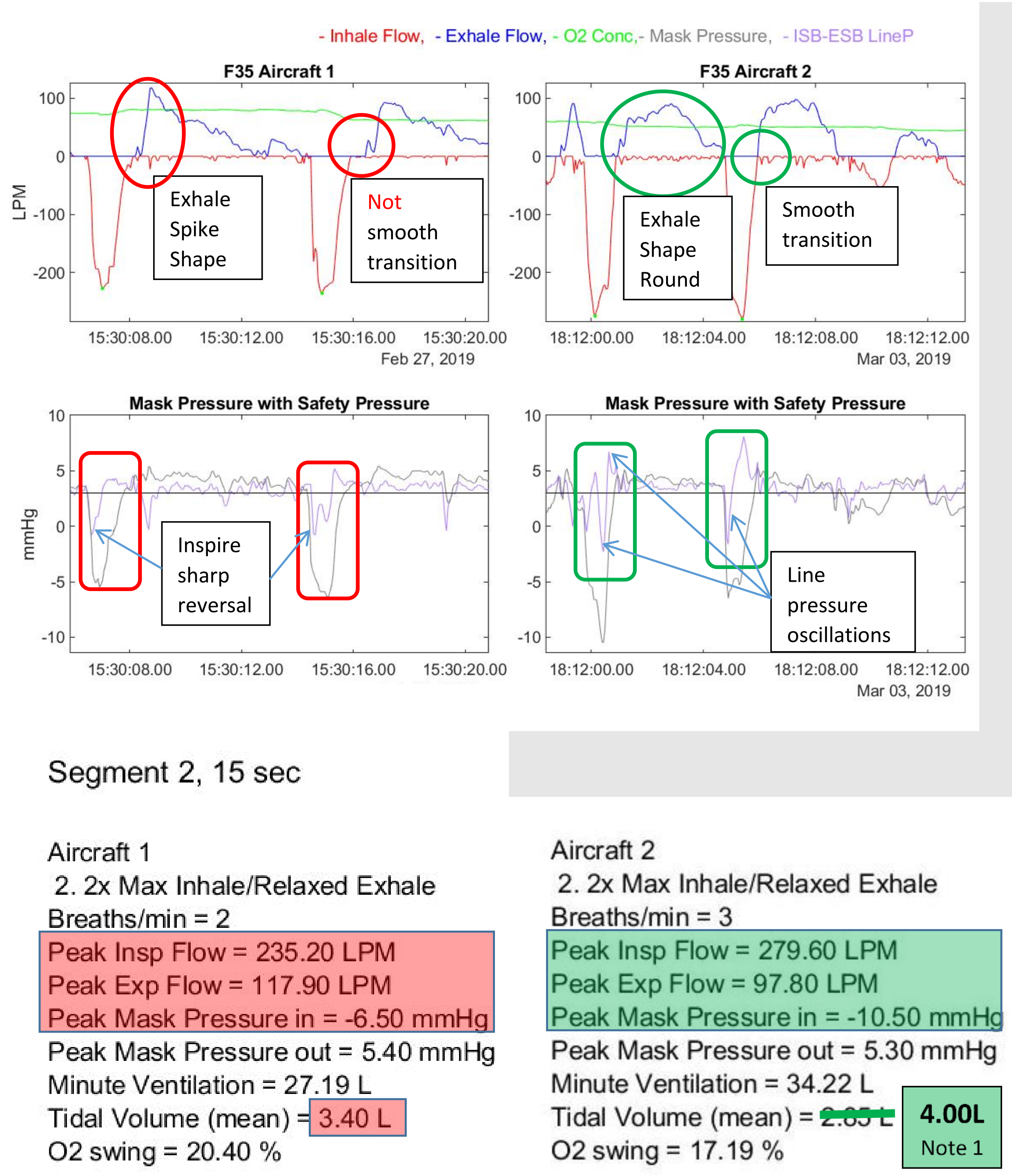


Figure 6.4. Maximum Inhale for both F-35 aircraft during Segment 2.

Note 1: In order to keep the time scale the same, both segments are 15 seconds long; that results in more than 2 breaths in the second window, lowering the average TV in the window. When recalculated with only the two Maximum Inhale breaths as is the intent of this segment, the TV is 4.00L

6.5 Effects of Backup Oxygen System (BOS)

The Backup Oxygen System in the F-35 is a high-pressure bottle completely independent of the OBOGS designed to supply 100% O_2 to the pilot for emergency use. This bottle supplies the pilot through the same regulator, which does not change functionality during normal operations. There is a failsafe which allows the BOS to bypass the regulator in a trickle flow mode, but that is not testable under normal circumstances.

A very important takeaway here is that many disruptive breathing patterns persist despite OBOGS being removed from the system. While this suggests that the OBOGS is not the primary source of the observed breathing anomalies, the OBOGS contribution to these dynamics should not be neglected. This is especially true for failure modes in the F-35 since the BOS waits to turn on until the plenum depletes, which makes for a very abrupt transition. The primary backup supply of O_2 is a critical part of the life support system, and its dynamics (including transitions) should not be neglected in testing. Drops in supply pressure are known to challenge regulators in general, and the worst time to have a disruptive breathing dynamic is at the very time when primary O_2 supply is at or near failing. OBOGS DEGD advisories and transition to and from BOS have occurred frequently in reported F-35 physiological events immediately prior to the onset of symptoms. It is also notable that BOS often does not resolve the symptoms immediately based on F-35 PE reports, indicating the primary problem is not O_2 concentration.

On Aircraft 1, (Figure 6.5) the mean TV is higher at 1.2L, yet the MV is lower at 11.98L due to a much lower respiration rate of 10 Breaths/min. Breathing dynamics are characterized by larger mask pressure swings and minimal separation between mask pressure and line pressure; mask pressure swings are from 5.2 to 2.9 mmHg in the green circle on Figure 6.3. As noted above, even with BOS activated and the OBOGS out of the loop, oscillations are present. In this case, vibrations during exhale predominate at 1.8 to 2Hz. Note the mask pressure does not have good separation from the line pressure and they frequently track together with swings of 1 to 2 mmHg several times during each exhale.

On Aircraft 2, (Figure 6.5) the mean TV is .84L (nominally the same as baseline in segment 1), and MV is 15.04L with a respiration rate of 18 Breaths/min. Breathing dynamics are characterized by less frequent oscillations of lower magnitude. Note the mask pressure has good separation during exhale with the line pressure staying at a nominal safety pressure of 3 mmHg. The mask pressure and line pressure occasionally track changes together, but the pressure swings are predominantly less than 1 mmHg.

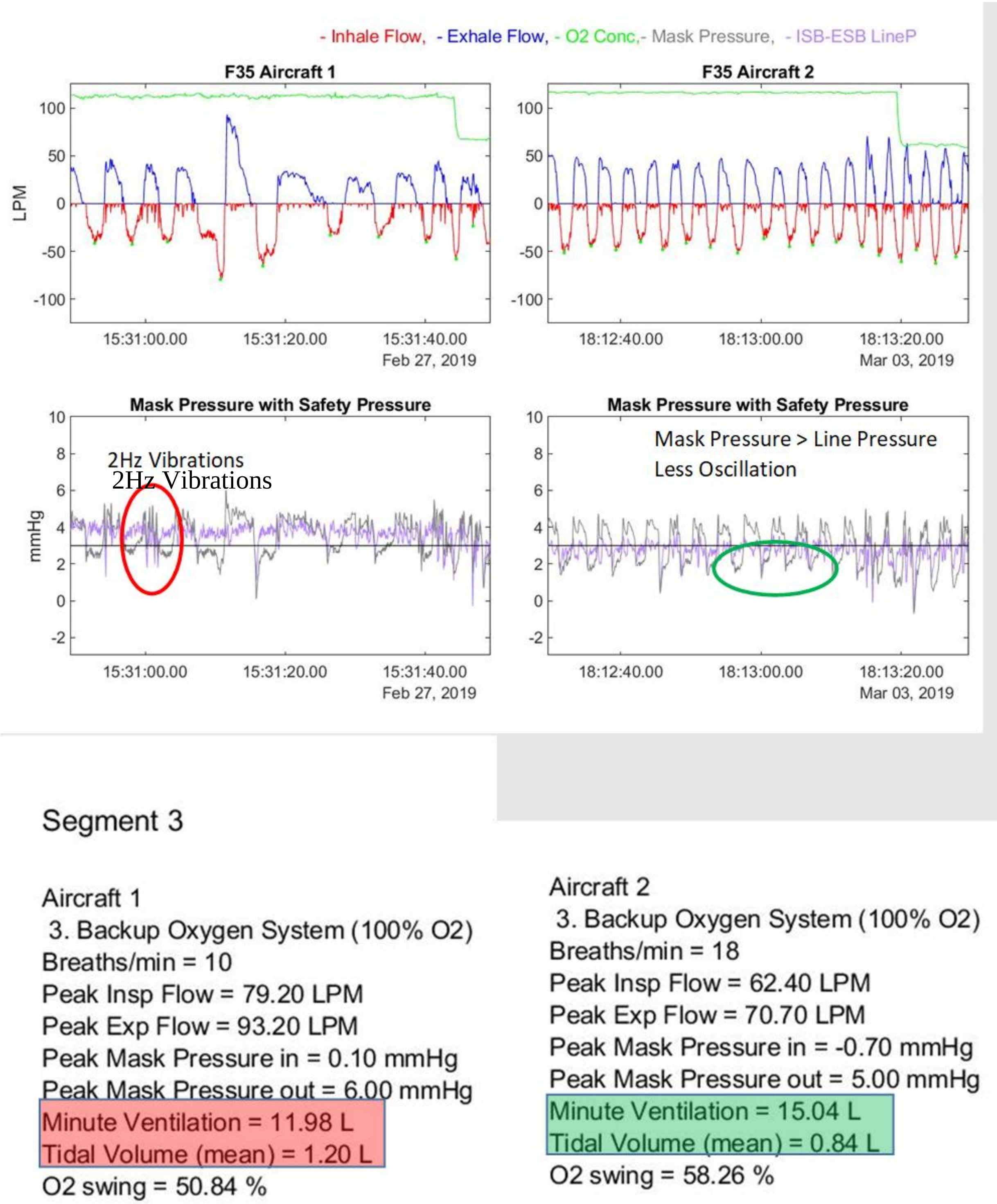


Figure 6.5. Backup O_2 System activated for both F-35 aircraft during Segment 3.

6.6 Effects of Defog On

The Defog system in the F-35 controls the temperature, distribution, and flow of the air entering the cockpit. The air temperature is increased the maximum amount, diverted to the canopy, and the flow is increased in order to defog the canopy or preheat it in order to prevent canopy fogging. Selecting defog has a noticeable impact on the pressurization of the cockpit with cabin pressure transiently exceeding several hundred feet of pressure change. There is a pronounced sensation of more difficult exhalation in the mask and breathing being constrained considerably, even after the transients stabilize.

The changes in breathing dynamics with the selection of defog were so remarkable and noticeable to the test pilot collecting this data that it drove the design of experiment selected for the segments and emphasis on system of systems interactions. Perception of differences in breathing are difficult enough for pilots given the overwhelming number of sensory inputs present in the cockpit and flight environment. A repeatable and reversible system interaction that causes a marked and noticeable change in breathing offers a unique opportunity to correlate sensations with data. As is discussed in more detail in the medical section, “Fit pilots are poor perceivers of decline in lung function hence need objective measures”. These sensations, though pronounced, are easy to miss, as their magnitude is dwarfed by far greater sensory inputs experienced continually such as the mild roll and G-forces present during every turn made in flight, let alone high G maneuvering.

On Aircraft 1, the mean TV is .62L (same as baseline), MV is 7.41L (lower than baseline), and Respiration Rate is 12 Breaths/min (lower than baseline). Breathing dynamics are characterized by low variability in peak flow and the smallest pressure swings of all segments with mask pressure never dropping below 1.2 mmHg, and usually not dropping below 2 mmHg. While the exhale mask pressures show good separation from the line pressure, inhale pressure drops are only slightly larger in magnitude than the pressure oscillations themselves.

On Aircraft 2, the mean TV is 1.00L (greater than baseline), MV is 13.02L (lower than baseline), and Respiration Rate is 13 Breaths/min (much lower than baseline). Breathing dynamics are characterized by sharp spikes down during inhalations and larger pressure swings.

For both aircraft, MV during this segment was impacted, and the lowest of all segments. While the sensation of difficult exhalation was pronounced and MV did decrease in both cases compared to baseline (1.4L and 3.3L, respectively), that decrease is not nearly as large compared to the difference between aircraft of 5.6L (43% decrease) in segment 4 (Figure 6.4). Despite the overall impression that Aircraft 1 was a “bad breather”, it should be noted that there was no particular sensation or indication to the pilot of the magnitude of differences between MV, underscoring the silent and unnoticed nature of many of these changes in breathing dynamics. It is troubling to consider the possibility that a potential decrease in minute ventilation up to 50% could present to a pilot as a sensation that was just a little bit off.

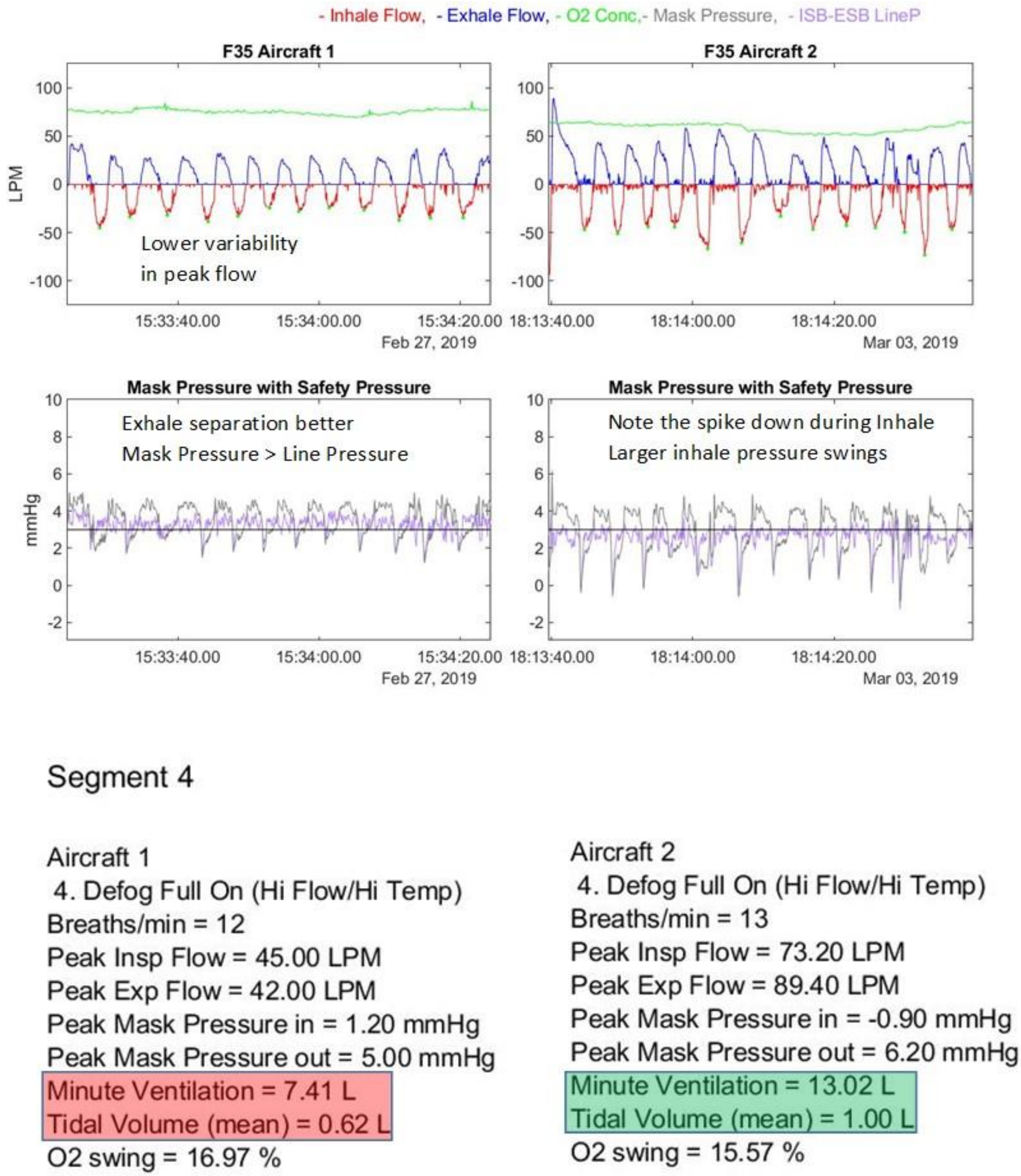


Figure 6.6. Defog activated for both F-35 aircraft during Segment 4.

6.7 Effects of G-Suit Interaction

The G-suit on the F-35 connects to the same regulator as the pilot's breathing system. The combined BRAG in the F-35 has a Press-To-Test function (PTT) which is used during normal checklist procedures to manually test the G-suit and mask prior to flight in order to ensure proper function. The PTT function is scheduled to deliver 18 inches of water gauge pressure to the pilot's mask, and 55.4 inches of water gauge pressure to the pilot's G-suit.

G-suits are not normally disconnected in an operational squadron; however depot operations require routine cross country sorties during deliveries of aircraft around the country, and these are generally accomplished without G-suits. During the course of flying dozens of these deliveries, with plenty of uninterrupted time for observation, it was noted by one pilot that the absence of the G-suit caused a material change to the breathing experience. The G-suit connection should not impact the breathing experience as the systems should operate independently; however, even though the pressure supply to the G-suit is entirely separate from the OBOGS pressure supply to the mask, they both connect through the BRAG in close proximity.

During PTT without a G-suit, the BRAG still attempts to inflate the non-existent G-suit. This causes air intended to inflate the G-suit to flow into the cockpit by the pilots left hip. PTT takes several seconds to reach full strength steady state pressure in the mask and G-suit, and since air was streaming out of the G-suit port, usually only held momentarily. Holding PTT for much longer than usual until pressures stabilized in this condition resulted in an observation of markedly lower mask pressure than was customary. This was found to be repeatable. Therefore, the G-suit was disconnected during these segments in order to understand why aircraft breathe different without a G-suit connected. PTT was also intended as a benchmark pressure since it is supposed to deliver 18 inches of water gauge pressure. If the G-suit port (Figure 6.5, Red Cap) is covered (essentially plugged with a thumb) during PTT while air is attempting to inflate the missing G-suit, the mask pressure instantly increases, and conversely, when the G-suit port is uncovered allowing air to flow freely, mask pressure decreases. This pressure difference is so large, that it is very easy for a pilot to sense.

> "The possibility of reduced bleed air pressure at the OBOGS generator reducing pressure at the regulator (due to G-suit air freely flowing into the cabin) appears to be ruled out entirely since the same effect occurs in BOS, which has nothing to do with OBOGS pressure. The second possibility appears to be what is happening; the regulator baseline or reference pressure appears to be skewed by the G-suit venting/plumbing" [Test Pilot original write-up submitted to F-35 program office]

Segments from this point on in the report are without the G-suit connected. Without the G-suit connected the pilot reported that the breathing dynamics were significantly improved on Aircraft 1.

Figure 6.7. G-suit (left), black electronic regulator [below a BOS bottle] (right), and mask (bottom). Both G-suit and mask connect to the BRAG [note that the mask shown is not an F-35 mask; the figure only depicts proper system connection locations].

6.8 PTT, G-suit connection and Mask Off/On

In Segment 5 (Figure 6.8, top), PTT was accomplished with the G-suit connected. The mask pressures stabilized at and slightly above 20 mmHg.

In Segment 7 (Figure 6.8, middle), PTT was accomplished without the G-suit connected on the left side of both graphs. The mask pressures stabilized 5 to 7 mmHg lower at 13 mmHg and 15 mmHg respectively for Aircraft 1 and Aircraft 2. When the G-suit port was covered and uncovered repeatedly, mask pressure in both aircraft increased by approximately 1 0 mmHg (Figure 6.6, middle). The right sides of the graphs, which show quick successive spikes and valleys, are where the port is plugged (covered) repeatedly.

In Segment 11 (Figure 6.8, bottom), after doffing the mask (middle section flat lines), it was difficult to restart flow on Aircraft 2. The first attempt to take a breath after donning the mask resulted in approximately -10 mmHg in both mask pressure and line pressure without any flow initially causing a distinct "sucking rubber" sensation. Negative 10 mmHg without any flow is a significant respiratory insult. This was true for Aircraft 2 in both Segment 5 and Segment 7 (circled in green). In both cases there was an unsuccessful attempt to initiate breathing during the first drop in pressure and a subsequent successful attempt on the second drop in pressure. Note that on Aircraft 1, this breathing dynamic was not present, and although the line pressure drops to -7 mmHg during the first attempt to inhale, the mask pressure remains steady at 0 mmHg, and flow started with minimal delay.

While Aircraft 2 was anecdotally described as the "good breather", this is one of several breathing dynamics during inhale that were less than desirable.

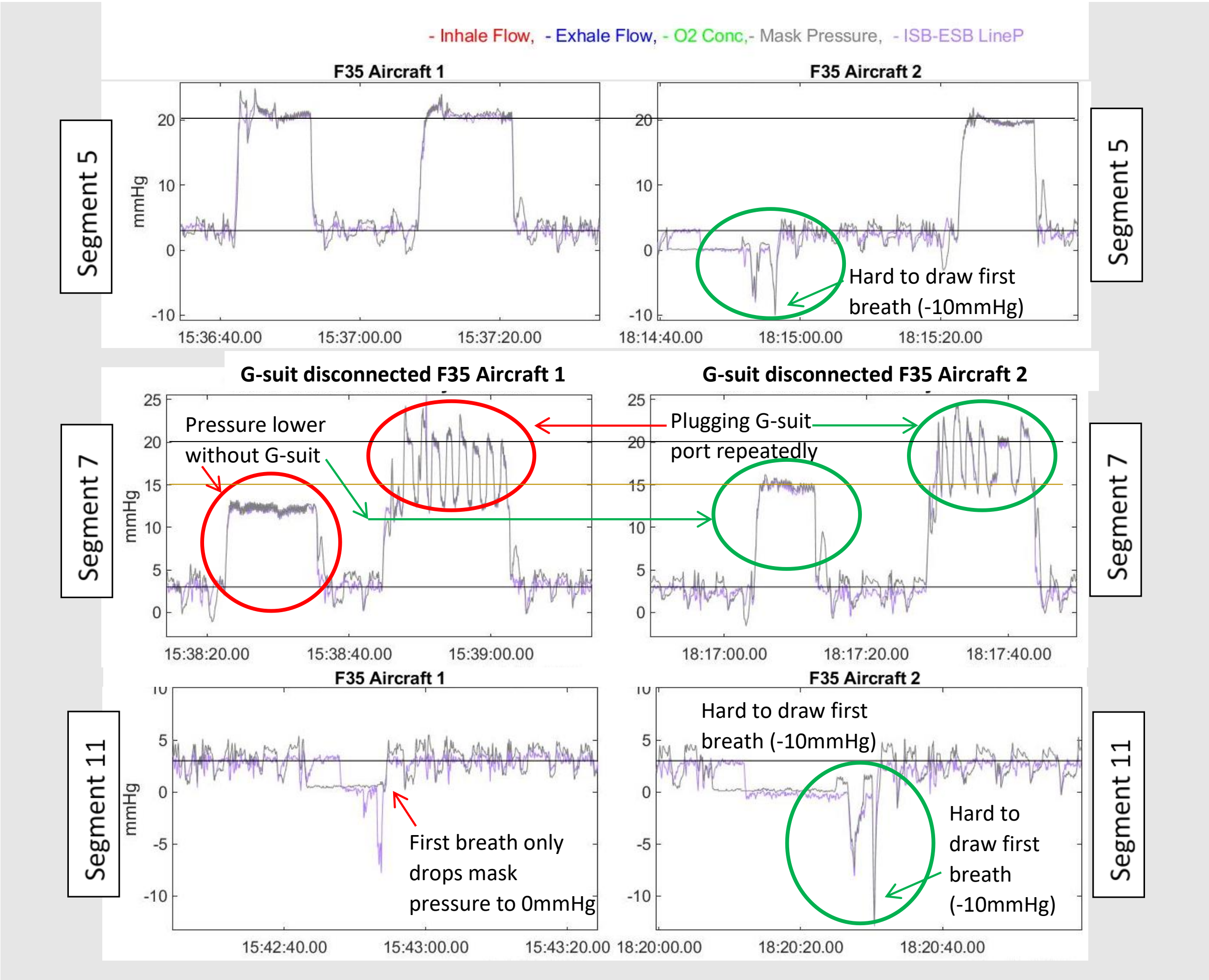


Figure 6.8. PTT with G-suit connected (top graph), PTT with G-suit disconnected (middle graph), Mask doffing with G-suit disconnected (bottom graph) for both F-35 aircraft during the respective Segments as labeled. (Top Right graph) also has Mask Doffing with G-suit connected.

A note about F-35 data quality: The developmental VigilOX units used in this test have been known to suffer occasional errors that introduce spikes into one recorded channel (not all simultaneously). In the present case, the data quality is helped by evaluating multiple channels together and explaining particular features in the data alongside pilot notes of perceptions during these short acquisition windows. Additionally, when compared to the subset of 24 F-18 and F-15 PBA flights taken with the same type of developmental unit, again, the differences between patterns in the three jet types are clear.

6.9 Effects of Maximum Inhale (without G-suit)

When the G-suit is disconnected the dynamic behaviors are different and it is easier to breathe. The intent of the maximum inhale segment followed by a relaxed exhale was to create a repeatable point (maximum inhale volume at maximum effort is fixed) in order to show comparative differences in breathing dynamics between aircraft and in the presence of system interactions. While changes in breathing dynamics without a G-suit are not operationally relevant and normally fall into the category of degraded systems operations, the underlying change in dynamics are an important pointer to fundamental systems dynamics and their impact on breathing.

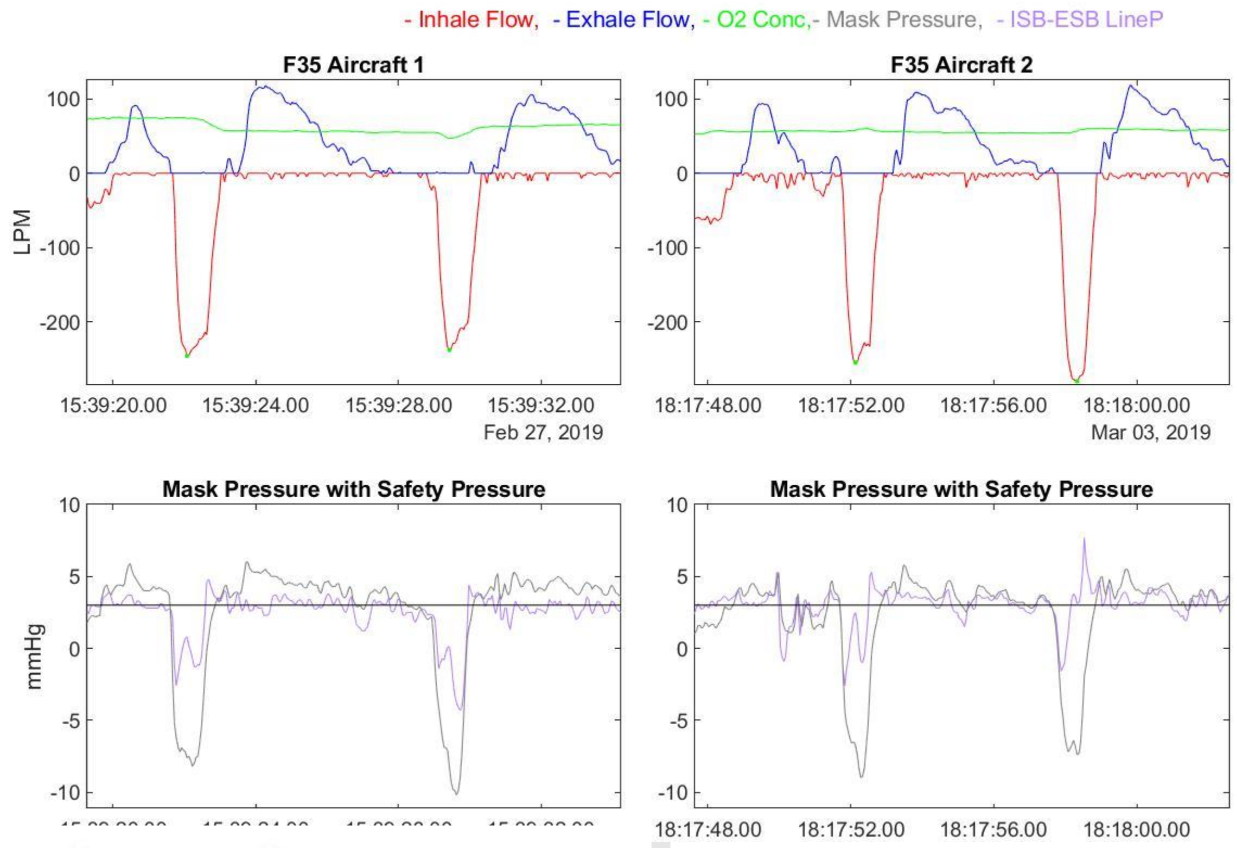
On Aircraft 1, the mean TV was 3.72. TV increased .32L above the 3.4L mean in Segment 2 with the G-suit connected. This was consistent with the pilots report of easier breathing with the G-suit disconnected. The breathing dynamics during exhale more closely resemble Aircraft 1. They are no longer characterized by a sharp exhale flow shape with an immediate peak. Flow still peaks early during exhale, but the shape is more rounded. While transitions from inhale to exhale are still not as smooth as Aircraft 2, the delay in transition to flow is decreased, and mask pressures are more commensurate with the resulting flow. Breathing dynamics during inhale are characterized by a drop in line pressure near -2.5 mmHg without a subsequent sharp return back to safety pressure as before.

On Aircraft 2, the mean TV was 3.98. This was essentially unchanged from 4.0L in Segment 2 with the G-suit disconnected. Aircraft 2 exhibited the largest line pressure oscillation in all of the data during Segment 2, and while oscillations are still present during inhale, they are now of lesser magnitude and lower frequency.

O_2 concentration drops during the first breath for Aircraft 1 by 28%, but increases on the second breath. On Aircraft 2 O_2 concentration remains steady, actually increasing after the two maximum inhales (green line in the top graph of Figure 6.9).

In comparison to Segment 2 with the G-suit connected, the data without the G-suit connected had overall better breathing dynamics; increased TV and decreased exhale resistance on Aircraft 1 and decreased inhale oscillations on Aircraft 2.

Until the development of hysteresis and phase shift metrics, a repeatable measure with the same pilot such as this was the closest substitute for an objective breathing metric. In addition, it is important to test the “corners of the envelope”, as aircraft breathing systems have a requirement to support breathing in the entire breathing envelope. Maximal Inhales elicited breathing dynamics not observed elsewhere in the data and should be considered essential for any end to end system testing.



Segment 8, 15 sec

Aircraft 1
8. 2x Max Inhale/Relaxed Exhale wo G-suit
Breaths/min = 104
Peak Insp Flow = 245.50 LPM
Peak Exp Flow = 117.90 LPM
Peak Mask Pressure in = -10.20 mmHg
Peak Mask Pressure out = 6.00 mmHg
Minute Ventilation = 29.74 L
Tidal Volume (mean) = 3.72 L
O2 swing = 28.78 %

Aircraft 2
8. 2x Max Inhale/Relaxed Exhale wo G-suit
Breaths/min = 14
Peak Insp Flow = 279.70 LPM
Peak Exp Flow = 118.60 LPM
Peak Mask Pressure in = -9.00 mmHg
Peak Mask Pressure out = 5.80 mmHg
Minute Ventilation = 31.88 L
Tidal Volume (mean) = 3.98 L
O2 swing = 8.33 %

Figure 6.9. Maximum Inhale for both F-35 aircraft during Segment 8.

6.10 Effects of Rapid, Deep Breaths (without G-suit)

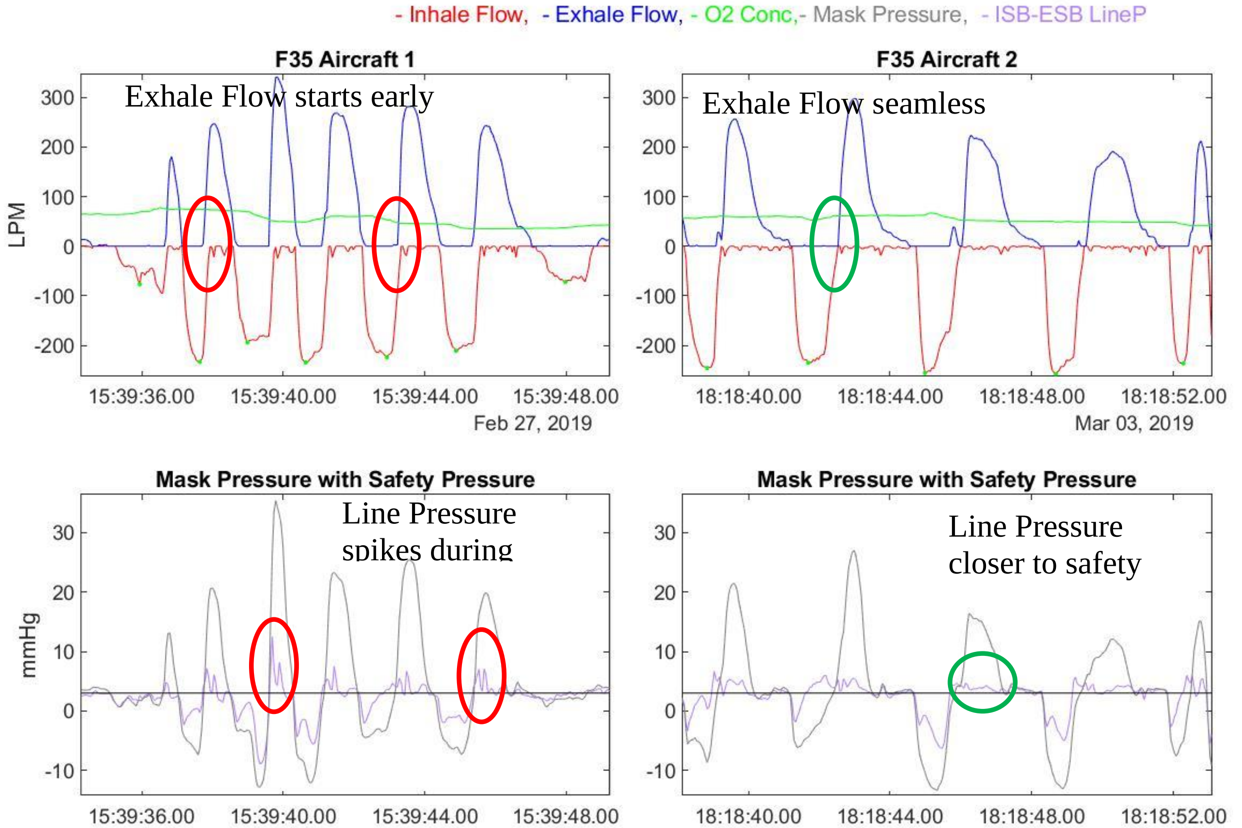
During Segment 9, the goal was not a maximal and repeatable inhale, but rather a continuous demand for a maximum amount of air. Instead of a relaxed exhale, here the exhales are forceful. Basically the goal was maximum effort, continuous breathing for 15 seconds, with no attempt to have a specifically defined rate or depth of breathing. Accordingly, no attempt is made to compare TVs, MV, or peak flows because of the inherent variability of the design.

On Aircraft 1, the breathing dynamics are characterized by spikes in the line pressure during exhale (Figure 6.10, bottom left) and inhale flow continuing during the beginning of exhale flow (Figure 6.10, top left) Conversely, this can be viewed as exhale flow beginning before inhale flow ends. Either way it appears as a gap of white space during the transition in flow from inhale to exhale. While this resembles an inhale valve malfunction, this only happens during this segment, and only on Aircraft 1. These points were accomplished with the same mask.

As discussed previously, when the inhale valve does not sequence closed properly, pressure can flow back down the line. That usually causes an ISB DFLR bit, but in this case there is no DFLR bit associated with Aircraft 1 during this Segment. The alternative is that both the flow from the regulator and the flow from the pilot can exit the exhale valve at the same time due to the overshooting pressure from the regulator. The second scenario is more consistent with the data, especially considering that the peak expiratory flow of 340LPM is the largest peak flow in all the data, and would not likely result with flow going back down the inhale line. Regardless, if both valves are open simultaneously as the data strongly suggest, neither breathing dynamic is healthy. Note the mask pressure in excess of 30 mmHg immediately after the line pressure dynamically overshoots past 10 mmHg. These values are in the range capable of causing barotrauma.

In addition, the extended high demand causes the O_2 concentration to drop 43% during this segment. Unfortunately from a physiology standpoint, poor breathing dynamics often line up with rapid changes in O_2 concentration. This is a good example.

On Aircraft 2, the breathing dynamics are characterized by smoother transitions to exhale with no gap (Figure 6.10, top right). Line pressures only marginally overshoot during exhalation (Figure 6.10, bottom right) and stay close to the nominal safety pressure value. The ISB DFLR bit was set for a period of less than .4 seconds during one exhale in this segment. O_2 drops 25% during this segment.



Segment 9, 15 sec

Aircraft 1
9. Rapid Deep Breaths (w/o G-suit)
Breaths/min = N/A
Peak Insp Flow = 234.30 LPM
Peak Exp Flow = 340.70 LPM
Peak Mask Pressure in = -12.80 mmHg
Peak Mask Pressure out = 35.40 mmHg
Minute Ventilation = 62.95 L
Tidal Volume (mean) = 2.25 L
O2 swing = 42.89 %

Aircraft 2
9. Rapid Deep Breaths (w/o G-suit)
Breaths/min = N/A
Peak Insp Flow = 257.50 LPM
Peak Exp Flow = 297.40 LPM
Peak Mask Pressure in = -13.40 mmHg
Peak Mask Pressure out = 27.00 mmHg
Minute Ventilation = 62.60 L
Tidal Volume (mean) = 3.13 L
O2 swing = 25.20 %

Figure 6.10. Rapid, deep breaths for both F-35 aircraft during Segment 9.

6.11 Effects of Increased Engine Power Setting (without G-suit)

In the F-35 at idle power, the OBOGS is supplied with a lower pressure from the ECS compared to increased power settings. The pressure of the air supplied to the OBOGS determines the pressure the OBOGS is able to supply the regulator, and hence can change the response characteristics of the regulator and resulting breathing dynamics. The F-35 does not use RPM or EGT to manage thrust like legacy aircraft, but rather uses the Expected Thrust Request (ETR). This is basically how much thrust is expected at the selected throttle position compared to the total thrust available as measured on a scale with 100% being Military Power (full power without afterburner). At idle on the ground, ETR is usually 10%, or 10% of total available thrust. 15% ETR is a significant increase in power as far as ECS bleed air is concerned, but still a nominal value used during normal ground operations. 15% ETR was selected during this segment.

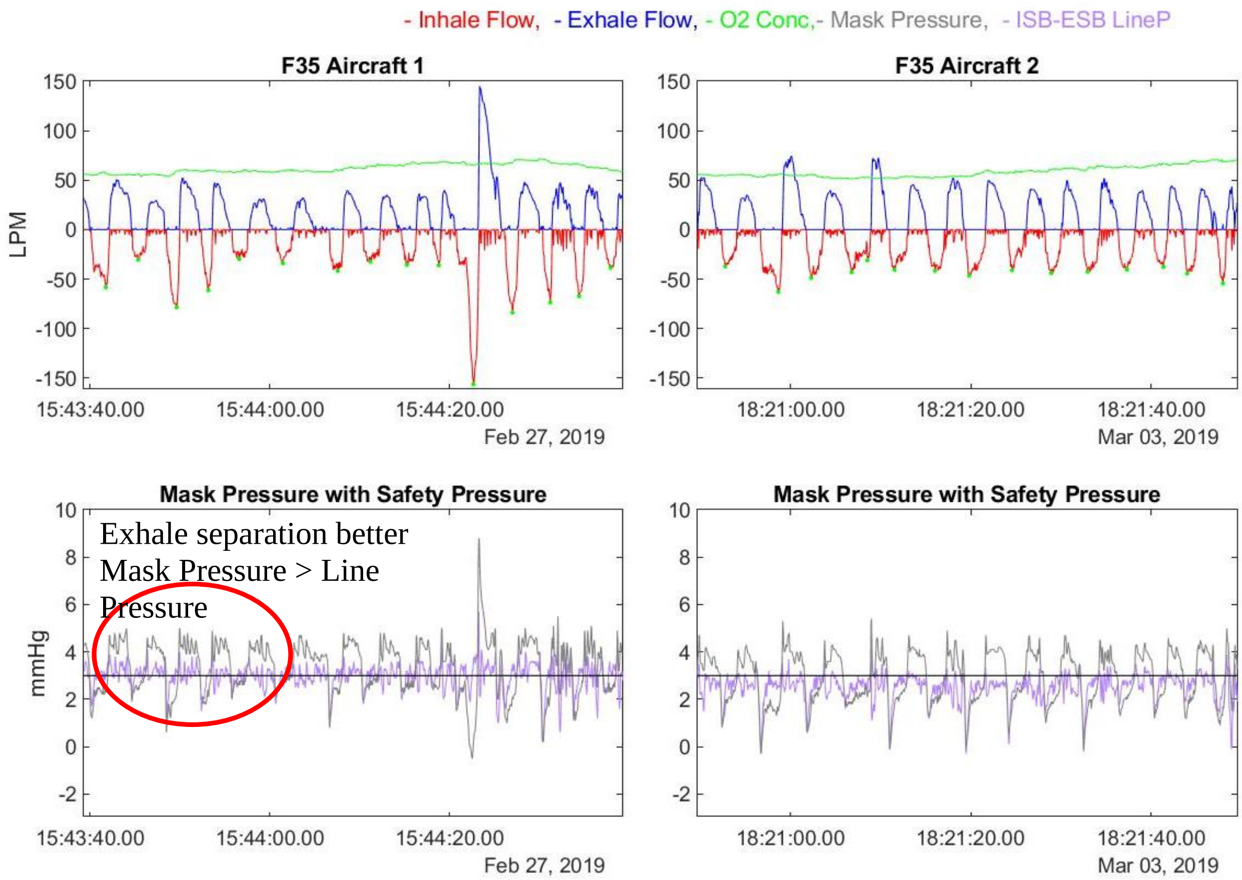
On Aircraft 1, the mean TV was .93L, the MV was 13.92L, and the Respiration Rate (RR) 15 breaths/min. The breathing dynamics are characterized by significantly improved separation between mask pressure and line pressure during exhale, and a concomitant increase in TV and MV. Compared to baseline in Segment 1, TV is increased from .63L, respiration rate is slightly increased from 14, and overall MV is increased from 8.79L (a 58% increase).

On Aircraft 2, the mean TV was .91L, the MV was 13.58L, and the RR was 15 breaths/min. Compared to baseline in Segment 1, TV is increased from .82L, respiration rate is decreased from 20 breaths/min, and overall MV is decreased from 16.36L. See Figure 6.11.

In comparison, Aircraft 1 and 2 are now essentially equal. Breathing dynamics result in TV, MV, and RR which are all nominally the same. Compared to baseline, Aircraft 1 has TV and MV which have increased approximately 50%. Compared to baseline, Aircraft 2 has MV and RR decreases of approximately 20%, with a TV increase of approximately 10%.

While Segment 1 was intended as a reference point for comparison and is herein called a baseline, it should not be confused with a true baseline of physiological values. Such a baseline does not currently exist and is not currently possible to ascertain accurately in the cockpit of any fighter or trainer aircraft. One of the main goals of the PBA is to create a database of pilot breathing on legacy aircraft for comparison. In other words, help answer the question, "What is normal breathing in a fighter?"

The trends and comparisons present in this data, however, still provide an information on system behavior.



Segment 12

Aircraft 1
12. Engine above Idle (15% w/o G-suit)
Breaths/min = 15
Peak Insp Flow = 156.30 LPM
Peak Exp Flow = 145.00 LPM
Peak Mask Pressure in = -0.50 mmHg
Peak Mask Pressure out = 8.80 mmHg
Minute Ventilation = 13.92 L
Tidal Volume (mean) = 0.93 L
O2 swing = 18.05 %

Aircraft 2
12. Engine above Idle (15%-w/o G-suit)
Breaths/min = 15
Peak Insp Flow = 62.80 LPM
Peak Exp Flow = 74.50 LPM
Peak Mask Pressure in = -0.30 mmHg
Peak Mask Pressure out = 5.40 mmHg
Minute Ventilation = 13.58 L
Tidal Volume (mean) = 0.91 L
O2 swing = 19.51 %

Figure 6.11. Increased Power Setting for both F-35 aircraft during Segment 12.

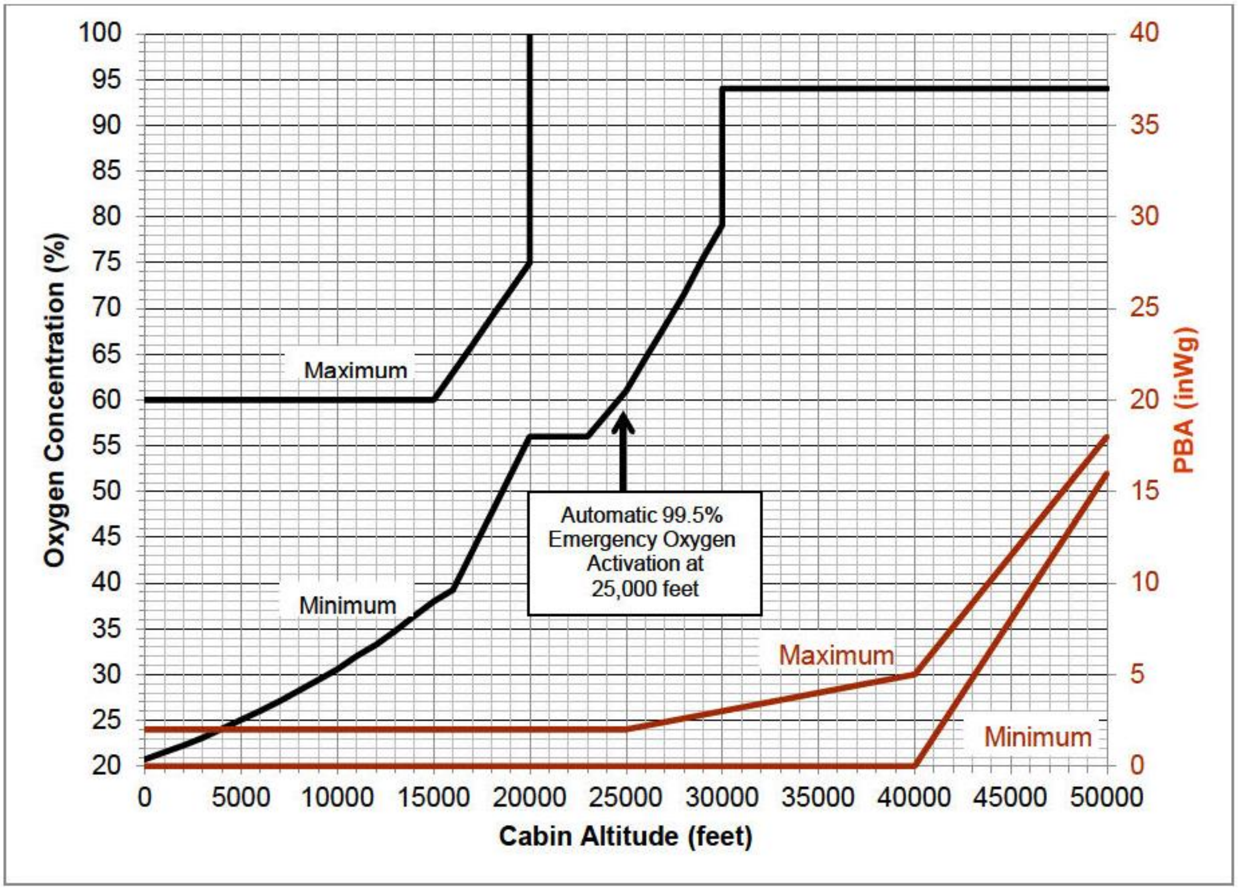


Figure 6.12. O_2 concentrations and regulator pressure schedule for an aircraft flying to 50.000 feet with a 5 psi differential pressure cabin.

7.0 Analysis of Reduction in Minute Ventilation

The goal of a breathing system is to provide an appropriate volume of air over time; hence the volume of air over one minute, minute ventilation (MV), is one of the most relevant parameters in analyzing breathing system impact on physiology. The data presented in Figure 7.1 (top three) were discussed in Section 6. Tables are presented here for ease of comparison. In summary, aircraft environmental settings and G-suit connections changed respiratory patterns (MV, TV, and respiration rate) by variable, inconsistent, and often physiologically significant amounts. On two separate F-35 aircraft, ground tests with the same pilot using similar scripts and with expected similar metabolic loads resulted in ~50% differences in measured MV and exhibited dissimilar breathing profiles.

There is a consistent pattern across all sensors and across all metrics (from individual breaths to distributions for the entire run) of lower TV, lower flows, longer times, lower respiration rates, and lower MV on Aircraft 1 compared to Aircraft 2. There are also considerable changes in observed MV corresponding with changes in aircraft systems; in other words system interactions between man and machine (Figure 7.1). While limited to two aircraft and several 1 minute segments of interest, which of necessity cannot be statistically representative of all aircraft or all pilots, the F-35 data refute the widely held assumption that aircraft breathing systems do not significantly affect pilot breathing physiology. Furthermore, these observations point to overall differences between the F-35's with respect to the legacy F-15 and F-18 aircraft in the main PBA report.

The differences between jets are not particularly surprising. Several pilots reported these differences:

- "I talked to [JPO individual] afterward, and they crunched the data in the jet…it was ascertained that during the period of time encompassing the physiologic event enumerated my minute ventilation, so the amount of oxygen/air I had consumed from the jet was about half of what would had been predicted."
- "I do think that the jet breathes differently or each tail number did at least have some subtle variations."
- "There is noticeable change between jets and some are easy breathers versus more difficult breathers."
- "[Aircraft 1] was definitely a 'Bad Breather', but nowhere close to the worst I've flown."

Pilot reports and data suggesting that decreases in MV up to 50% can occur almost without notice, present to a pilot as feeling just a little off, and be of such magnitude in an aircraft "nowhere close to the worst", is troubling from a detection and reporting viewpoint.

Metabolic demand is ordinarily the primary determinant of MV (e.g., muscular exertion causes elevated breathing and higher MV), so data were taken during relaxed breathing while sitting, where metabolic demand is minimal. Changes to MV in the absence of changes to metabolic demand are indicative of aircraft breathing systems exerting influence on pilot breathing. A useful reference point may be the CPAP (Continuous Positive Airway Pressure) breathing machine which many people are familiar with for sleep apnea. In the absence of metabolic changes, changes to MV while breathing on a CPAP are due to the influences of the breathing system controlling breathing. In other words, large breathing changes in one minute while sitting (no increase in exertion) are not likely caused by metabolic changes; they are caused by the aircraft breathing system. Therefore, MV was calculated as the simplest approximation of breathing system performance with changes to this value considered an indication of impact to pilot breathing physiology.

The data in Figure 7.1 (bottom) is a summary table of results that will be analyzed in this section. MV is a convenient summary statistic; however, it has inherently more error as a calculated value as it is not measured directly. Therefore, it is important to view this data in the context of all the available evidence, which as will be seen, all show trends pointing at the same conclusion. The redundant sensors on the VigilOX allow for multiple comparative analyses of slightly different aspects of breathing parameters: Two independent flow sensors, two independent line pressure sensors, a mask pressure sensor, two different time clocks all combine to allow for a robust comparison of flow rates, tidal volumes, and breath times. This redundant, multi-faceted approach gives greater confidence to the analysis than can be placed in one single calculated value of MV. Ultimately, the goal of a breathing system is to provide an appropriate volume of air over time; hence it is still the most relevant value in analyzing and summarizing the impact of breathing dynamics on pilot physiology.

MV per Aircraft per Segment [Segment Number – Name]	Aircraft 2 "Normal Breather"	Aircraft 1 "Bad Breather"	Difference
#1 – Normal Relaxed Breathing (Baseline)	16.4L/min	8.8 L/min	7.4L (-47%)
#3 – Backup Oxygen System (100% O2)	15.0L/min	12.0 L/min	3.0L (-20%)
#4 – Defog Full On (with G-suit)	13.0L/min	7.4 L/min	5.6L (-44%)
#10 – Defog Full On (w/o G-suit)	13.2L/min	11.5 L/min	1.7L (-13%)
#12 – Engine Thrust ETR 15% (w/o G-suit)	13.6L/min	13.9 L/min	0.3L (+2%)

Aircraft 1 MV Increases with systems changes	Aircraft 1 System	Aircraft 1 Baseline	Difference
#1 – Normal Relaxed Breathing (Baseline)	8.8 L/min	8.8 L/min	N/A
#4 – Defog Full On (with G-suit)	7.4 L/min	8.8 L/min	1.4L (-16%)
#10 – Defog Full On (w/o G-suit)	11.5 L/min	8.8 L/min	2.7L (+31%)
#3 – Backup Oxygen System (100% O2)	12.0 L/min	8.8 L/min	3.2L (+36%)
#12 – Engine Thrust ETR 15% (w/o G-suit)	13.9 L/min	8.8 L/min	5.1L (+58%)

Aircraft 2 MV Decrements with systems changes	Aircraft 2 System	Aircraft 2 Baseline	Difference
#1 – Normal Relaxed Breathing (Baseline)	16.4 L/min	16.4 L/min	N/A
#3 – Backup Oxygen System (100% O2)	15.0 L/min	16.4 L/min	1.4L (-9%)
#12 – Engine Thrust ETR 15% (w/o G-suit)	13.6 L/min	16.4 L/min	1.8L (-17%)
#10 – Defog Full On (w/o G-suit)	13.2 L/min	16.4 L/min	2.2L (-20%)
#4 – Defog Full On (with G-suit)	13.0 L/min	16.4 L/min	3.4L (-21%)

Consistent pattern of lower TV on Aircraft 1 compared to Aircraft 2 Shown by multiple metrics calculated from individual breaths up to the entire run			
Histograms of TV	**Relaxed TV/Flow**	**Maximum TV**	**Peak Inspire Flow**
Inhale Tidal Volume Peak	**Average TV Per Breath**	**Maximum TV (with G-suit)**	**Peak Inspire Flow (with G-suit)**
Aircraft 1 **.7 L**	Aircraft 1 **.63 L**	Aircraft 1 **3.40 L**	Aircraft 1 **235 LPM**
Aircraft 2 **.9 L**	Aircraft 2 **.82 L**	Aircraft 2 **4.00 L**	Aircraft 2 **280 LPM**
Exhale Tidal Volume Peak	**Inhale Flow Peak**	**Maximum TV (w/o G-suit)**	**Peak Inspire Flow (w/o G-suit)**
Aircraft 1 **.6 L**	Aircraft 1 **30-40 LPM**	Aircraft 1 **3.72 L**	Aircraft 1 **246 LPM**
Aircraft 2 **.8 L**	Aircraft 2 **30-70 LPM**	Aircraft 2 **3.98 L**	Aircraft 2 **280 LPM**
20% Lower TV on Aircraft 1	**25% Lower TV on Aircraft 1**	**15% Lower Max TV on Aircraft 1**	**15% Lower Peak Flow on Aircraft 1**

Figure 7.1. Reductions in Minute Ventilation Summary Tables

Tidal Volumes

Unlike laboratory settings where many of the equipment check-out procedures are initially performed, the cockpit environment (air and ground) is much more demanding. As such, real-world measurement data tend to exhibit more variability than their bench-test counterparts. This requires visualizing data within the context of larger trends rather than individual point comparisons. Histograms (frequency distributions) represent a valuable tool in describing complex measurements.

Breathe Time Distributions

Changes to breath times indicate breathing system impact on pilot physiology. Longer exhale times correspond with higher cracking pressures and flow restrictions. Longer inhale times correspond with lags in flow during the start of breathing demonstrated in Section 5.

Breathe Ratio (Inhale time compared to Total Time)

Breath Ratios are another general metric, applied here to assess changes in the pilots breathing dynamic. These breath ratios show a systematic difference between the two aircraft characterized by longer exhale times on Aircraft 1. Inhale to Exhale ratios are commonly used in respiratory physiology. They are important during mechanical ventilation as a control parameter and are also discussed in Section 5. Normal I/E ratios are 1:2 (.33 Breath Ratio), and with safety pressure I/E ratios of 1:1 (.5 Ratio) are not unexpected. As a point of reference, during mechanical ventilation, abnormal I/E ratios are uncomfortable and often require sedation of the patient. In room air, it takes about twice as long to exhale as it does to inhale due to the passive nature of exhalation, resulting in the common I/E ratio of 1:2 found in respiratory literature. A mask with safety pressure is similar to a mechanical ventilator, so similar changes to the I/E ratio are expected.

The Breath Ratio calculated here is not strictly speaking an "I/E ratio", instead it is the inhale time compared to the total time of that breath. Exhale times as discussed above are unreliable due to the pervasive disruptions to exhale flow present in the F-35. However, inhale times are distinct, and the time from one inhale to the next can be reliably calculated. Here the inhale time is divided by the total time from the start of one inhale to the start of the next inhale, or the total time of the breath. These values approximate an I/E ratio and become exactly equivalent when the exhale time is equal to the time between inhales.

Comparing the two aircraft in Figure 7.2, we see that the breath ratio is much lower for Aircraft 1, up to 50% longer exhalation time than inhale time. Aircraft 1 has an average ratio of approximately .43 (43% inhale/57% assumed exhale) and drops as low as .3 (30% inhale/70% assumed exhale) on two separate occasions. Given the longer exhale times in Figure 7.3, this result is not surprising, but helps put into context the relationship between the two times and relative differences at a glance over the entire duration of the test.

In contrast, Aircraft 2 has an average ratio of approximately .5 (50% inhale/50% exhale). In the context of safety pressure, the higher ratios are not unexpected due to the relative ease of effort during inhale (safety pressure), and relative difficulty of exhale prohibiting the normal passive mode of exhalation. The ratio on Aircraft 2 went as high as .6 (60% inhale/40% assumed exhale) on three occasions.

This is another metric showing a systemic difference between the two aircraft, and points towards significantly longer comparative exhale breathe times on Aircraft 1.

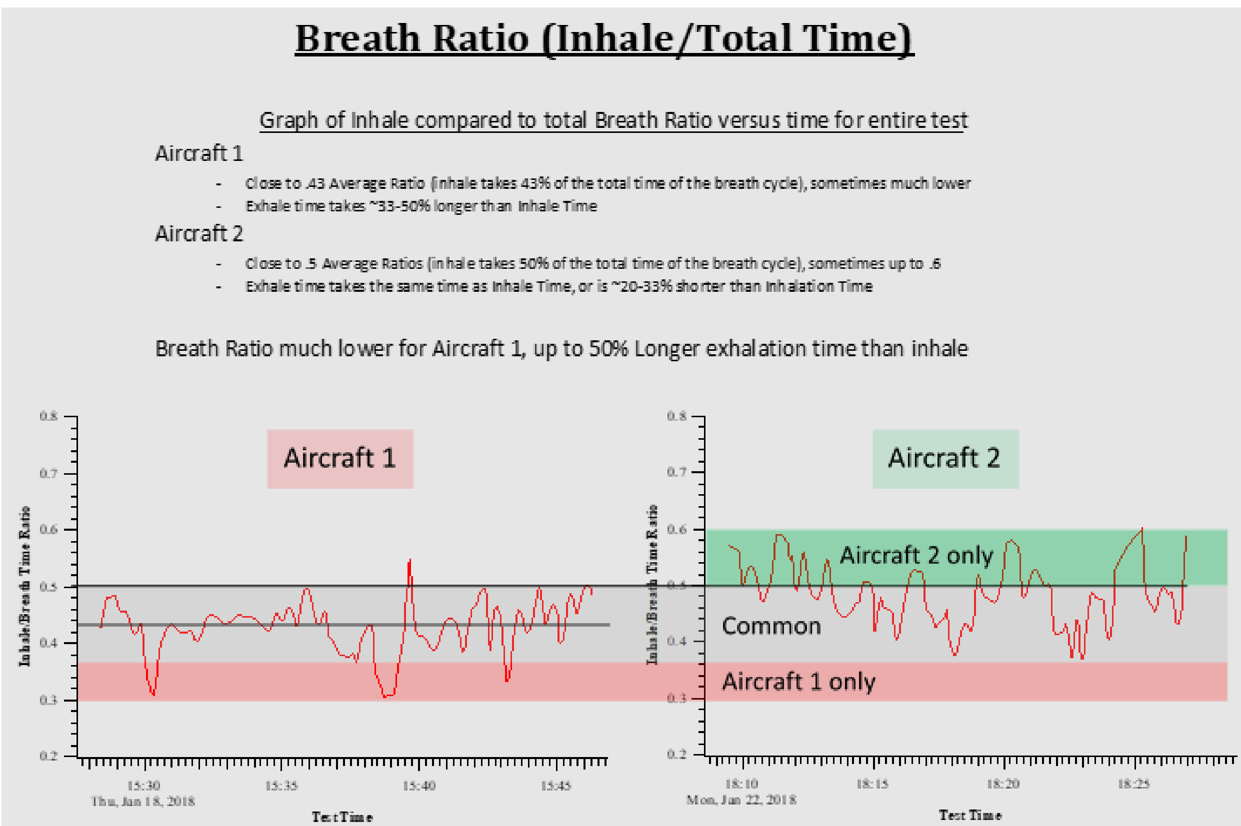


Figure 7.2. Breath Ratio Comparison Plots of Aircraft 1 and Aircraft 2

Inhale Time-to-50% Volume

Like the concept of phase shift, inhale time to 50% of final volume is another way to see the relative time sequence of events during the course of a single particular breath. The longer it takes to get to 50% volume the less air is received when the muscles are at their greatest mechanical advantage during the first half of inhalation.

Because of the extensive lag in the flow seen during the start of inhale, and the overshoot in pressure/flow during the second half of the breath, this was considered as a way to gauge the overall impact of those dynamics and quantify their magnitude and frequency. Simply timing how long it takes to get to 50% volume (Figure 7.5, left side graphs) is one potential measure of delay, but suffers from the difficulty inherent in stochastic breathing. Is the longer time due to lag or due to a longer breath? To alleviate that concern, the times are normalized by the time of the breath (Figure 7.3, right side graphs)

For sinusoidal breathing half way through a breath, the volume should be half way to its total as well. This equates to a relative Time-to-50% of .5 (dimensionless ratio of Time-to-50% divided by total breath time). Values below .5 indicate the flow arrives early in the breath and 50% volume is reached before 50% of the time. There are relatively few instances significantly below the .5 ratio and the distribution tails off quickly for front loaded breaths past a .4 ratio. Conversely, values above .5 indicate the flow arrives late in the breath and 50% volume is reached, in many cases, well after the half way point in the breath.

PBA ground testing of pilots with a medical-grade spirometer has shown an average value slightly greater than 0.4 with a tight distribution around the mean and values rarely, if ever, exceeding 0.50. This was accomplished during preflight in room air with no flight equipment. Flight data from PBA for nominal tests (no reported breathing difficulties, mask anomalies, etc.) show values that have a mean of approximately 0.50 with a tight distribution about the mean and values rarely, if ever, exceeding 0.60.

On Aircraft 1, 40% of the distribution is above a .6 ratio, with flow arriving very late in breathing sequence), and the distribution continuing well past a .8 ratio. On Aircraft 2, only 20% of the distribution is above a .6 ratio, and the tail of the distribution is much smaller, tapering off just after a .7 ratio. Concordantly, the actual time-to-50% volume was longer for Aircraft 1 at 1.15 seconds than the comparable time in Aircraft 2 of .85 seconds.

This is a significant indication of delayed flow response during the time sequence of a normal breath. Both aircraft exhibit this delayed flow (phase lag), as detailed in Section 5 on breathing dynamics. By this measure, Aircraft 2 is 20% worse with more breaths having flow arrive 10-30% later during the time sequence of an inhaled breath than a comparable evenly distributed breath would be expected to arrive.

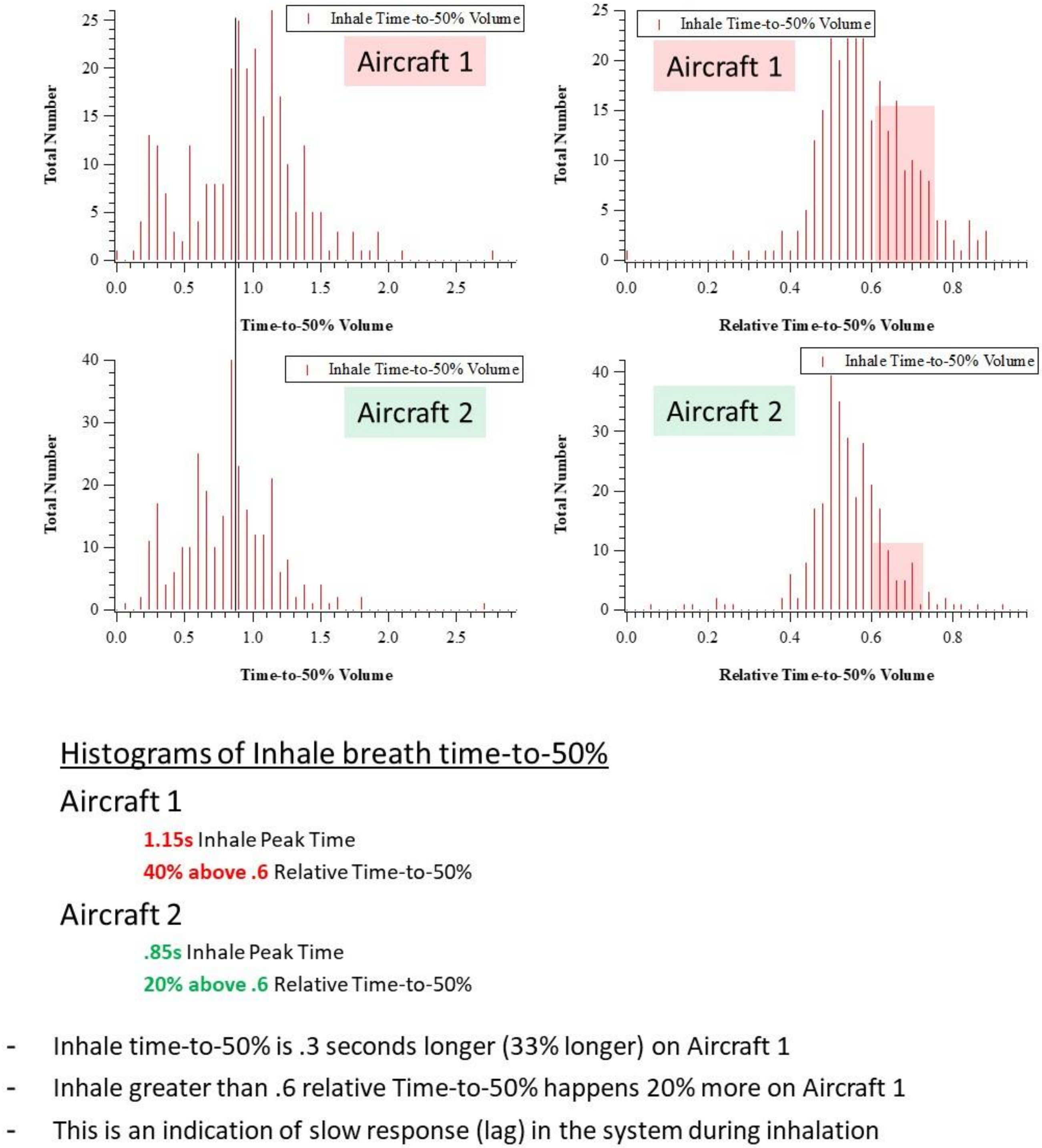


Figure 7.3. Inhale Time-to-50% Volume

Respiration Rate

Pilot respiration rate was measured and is displayed in Figure 10-4. The respiration rate for the pilot in Aircraft 1 was consistently less over the course of the profile compared to Aircraft 2. This is consistent with the individual histograms of inhale/exhale times. Longer inhale/exhale times result in a lower respiration rate since longer total time per breath results in fewer breaths per minute. This presentation gives a better overview of the entire sortie at a glance for direct comparison as opposed to individual breaths. This metric also indicates a systematic trend with Aircraft 1 having significantly lower respiration rate (longer time per breath on average) than Aircraft 2.

In summary, the anecdotally reported differences between jets and reports of reduction in minute ventilation are supported by this data. There is a consistent pattern across sensors and metrics indicating significantly lower TV, lower flows, longer times, lower respiration rates, and lower MV on Aircraft 1 compared to Aircraft 2 for breathing profiles that were expected to be similar.

On two separate F-35 aircraft, ground tests with similar scripts and expected similar metabolic loads resulted in >50% changes in minute ventilation and dissimilar breathing profiles. This is consistent with a pilot interview statement regarding the calculations made by the program office on data observed during a physiological event.

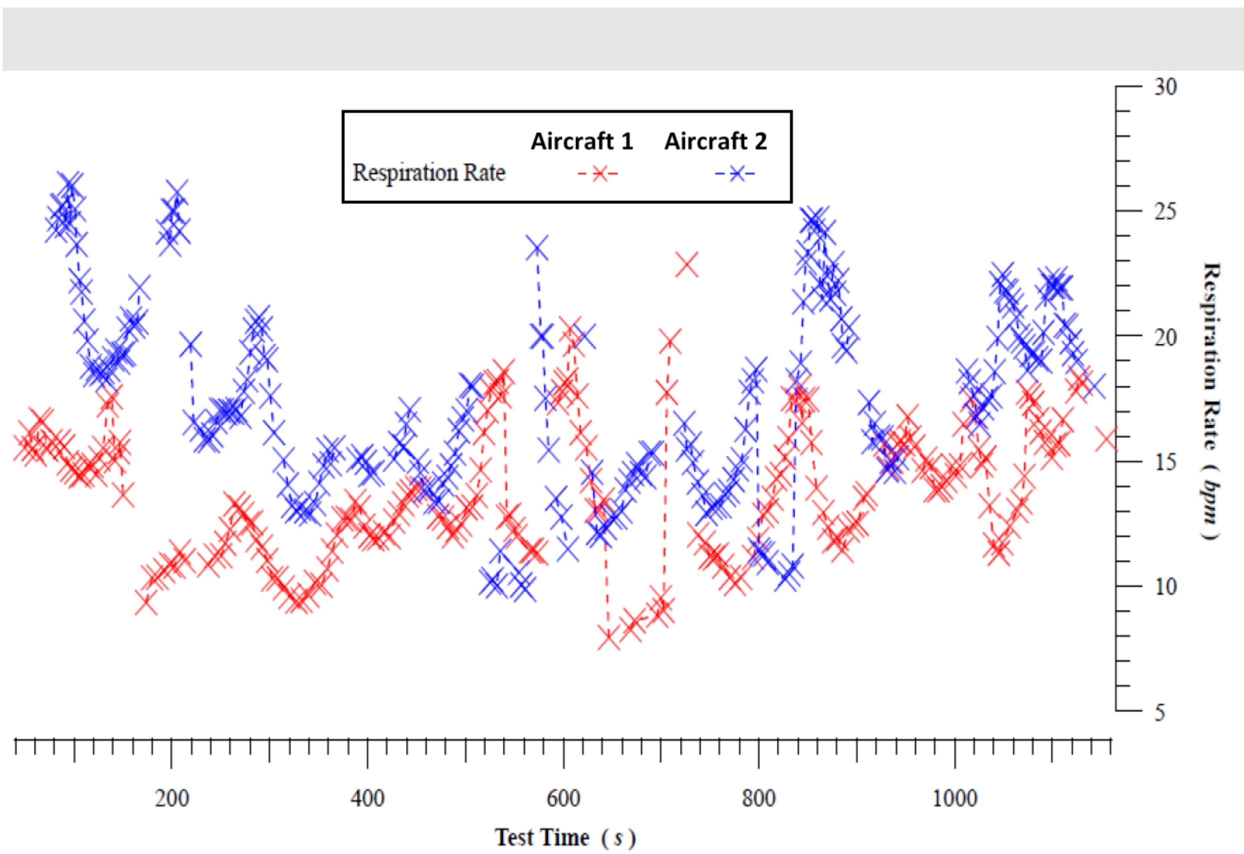


Figure 7.4. Pilot Respiration rate from measured data for the two F-35 aircraft. Note that the pilot in Aircraft 1 consistently has less respiration than in Aircraft 2.

8.0 Physiological and Medical Implications

The engineering design consideration of any breathing gas system of a high-performance aircraft is simple in concept: provide sufficient O_2 (flow, volume, concentration) to prevent hypoxia and other hypoxia-like symptomology. In practice, the dynamic range and response characteristics of those systems may be insufficient to sustain optimal physiologic function during high-performance flight, and hypoxia is not the only adverse pathology to be avoided. To match the highly variable human physiology to the machine is a highly complex process which, as will be demonstrated in this discussion below, is deceptively difficult and may inadvertently evoke unforeseen technical issues capable of compromising intended function of the breathing systems of the F-35. The current breathing system imposes an excessive burden of physiological adaptation on the pilot, resulting in adverse and undesirable physiological changes which often will go unnoticed or barely perceived. The body will attempt to respond within the confines of the system, but the response may be inadequate.

The numerous and pervasive technical issues discussed previously can contribute significantly to the acute emergence of adverse in-flight performance-degrading physiological symptoms. Up to 50% of F-35 pilots have experienced undesirable symptoms at least once, according to interviews. Many milder cases often go unreported, with abnormal in-flight symptoms dismissed or marginalized as ‘normal’. The accounts of normalization of deviation for in-flight symptoms during interviews are similar to what has been documented in the F-22 community. In more severe cases, the aircraft is actively causing acute injury, which, in rare but concerning instances, has demonstrated the potential for permanent disability. At least one pilot has been medically retired from military service with demonstrated pulmonary changes from his service entry.

The subtle, but pervasive nature of these physiological impacts, should not be overlooked, as in the following reports from Pilot interviews:

- “The most important observation to convey is the impact on pilot performance. Cognitive ability, fatigue, and overall performance are degraded without acute symptoms…repeated firsthand experience with excessive/chronic fatigue over 4 years of flying F-35s leads me to the conclusion that pilots are subjected to a physiologically compromising environment on a frequent basis resulting in sub-optimal performance and excessive fatigue not just during flight, but also cumulatively over time and over many flights.”
- Pilot: “…I was experiencing nausea, call it low-grade. It’s actually something I get in the jet fairly routinely…”

  Interviewer: “Going over that, how often do you get it? Every flight? Or, is there any associated symptoms with getting nausea in the aircraft?”

  Pilot: “Not every flight, frequently enough that it doesn’t surprise me that a low-grade, call it 2 or 3 out of 10, nausea after a longer flight. It happens enough that I’m not surprised by it.”

  Interviewer: “You said you had Viper [F-16] experience; any of that symptomatology in the Viper?

  Pilot: “No, none whatsoever. Never had it [nausea] in any other aircraft.”

In order to forge a more thorough understanding of the implications of pilot reports above, it is crucial to develop a foundational model of normal human respiratory physiology and how this physiology reacts when exposed to the cockpit environment: high altitude, high O_2 tension, and high forces of acceleration. The effects that any one of these in-flight conditions has on diminishing respiratory function cannot be understated. It may be best to think of human respiration, particularly in-flight, as a dynamically dynamic system; it can tolerate and adapt to certain deviations to a limit. The body will respond to changes to restore homeostasis through a multitude of mechanisms to be discussed, but its ability to compensate is finite. The goal of a breathing system is to stay safely away from the boundaries of these finite limits. However, any breathing system built around ground-tested, best case breathing parameters will always fail to account for the omnipresent effects that any in-flight perturbations away from ‘normal’ can have.

The aforementioned data collected during ground testing demonstrates the concerning changes in physiological parameters that the F-35 breathing gas system has on the human respiratory system across all phases of flight. These respiratory changes can cause a variety of often non-specific symptoms like those of Pilot 4 above. In more severe cases, these respiratory changes will result in reduced performance or incapacitation.

It should be noted that this section draws heavily from the Aircrew Breathing main report, but does concentrate on the specifics and findings in the F-35 ground runs.

8.1 Physiology

Skeletal-Muscular injuries due to the effects of G’s, seat position, and helmet weight, especially on the back, spine, and neck are well documented. Pilots and Flight Surgeons are rightfully sensitive to minor trauma from these issues because of the known cumulative damage and long-term disability that historically results. There is currently very little sensitivity to respiratory muscular trauma or insults to lung function. Unlike a sore neck, pilots and general physicians are not accustomed to recognizing the symptoms nor thinking about the physiological consequences of muscular trauma to respiratory function. While a sore neck is painfully obvious and makes head movement difficult, traumatized respiratory muscles rarely draw notice, yet have a far greater impact on our ability to function at peak performance. Poor lung function affects all aspects of physiology; poor function due to muscle trauma elsewhere does not. As the Air Force Chief of Pulmonary Medicine said, “Fit pilots are poor perceivers of decline in lung function hence need objective measures” (Lt Col Dara Regn, MD, USAF, MC, FS, Chief, Pulmonary and Sleep Medicine Aeromedical Consultation Service. E-mail correspondence April 9 2020) and studies note that elite athletes “symptoms have been shown to be poor predictors” of breathing problem diagnosis (Couto et. al) It is difficult to mitigate imperceptible, minimally perceptible but unaddressed, and unrecognized declines in physiological function. Hence it is critically important for those developing standards and requirements to have a thorough understanding of respiratory physiology.

__Breathing__, or more precisely, ventilation, is an automatic, rhythmic, and neutrally-regulated mechanical process. The contraction and relaxation of the skeletal muscles of the diaphragm, abdomen, and rib cage cause gas to move into and out of the alveoli of the lung. The human respiratory cycle is tightly controlled by central and peripheral nervous system chemoreceptors which respond to local concentrations of carbon dioxide (pCO_2), oxygen (pO_2) and acidity (pH). At rest, an averaged sized male will consume 0.34 L (STPD)/min of O_2. Through chemoregulatory control, this will increase to 1.00 L (STPD)/min of O_2 consumption during strenuous tasks such as air combat maneuvering. (Loer et al) To provide this drastic increase in O_2 requirement and to offload all the resultant CO_2 produced, the body will alter volumes and rates to achieve desired ventilation, or movement of air.

__Inspiration__ is the active phase of breathing and is initiated by neural influences from the respiratory control centers in the brainstem. During inspiration, the diaphragm along with the intercostal muscles contract which, in turn, cause the thoracic cavity to expand. As the thoracic cavity expands, the distensible lungs passively expand. The surface of the lung is coupled to the thoracic cavity by a thin layer of liquid. The liquid coupling allows the lung to "move" during breathing and to adapt to the shape of the thorax.

As the thoracic cavity expands, the pressure in the terminal air spaces (alveolar ducts and alveoli) decreases. Once the pressure in the thorax decreases to a subatmospheric level, fresh air flows down the branching airways and into the terminal air spaces. As the pressure in the airways equalizes with the atmospheric pressure, inspiration ends.

The inspiratory muscles work against resistance: the elasticity of the lungs, the airway resistance, and the resistance of the chest wall. All of these are altered in the cockpit environment; the shape of the lungs adapts to the same shape as that of the thoracic cavity. If thoracic size is temporarily reduced, (e.g., cockpit posture, flight gear, harness, etc.) lung size is also reduced. This will alter the natural breathing rhythm or cadence and increase the work of breathing and can lead to a variety of symptoms such dyspnea or breathlessness. Impedance to inspiration will increase the negative pressure inside the lung and result in under-ventilation.

Expiration is generally more passive compared to the active muscle recruitment during inspiration. During expiration, the elastic recoil properties of the lung and decreasing size of the thoracic cavity cause pleural and alveolar pressures to rise to greater than atmospheric level. Consequently, gas flows out of the lung and continues to do so until the pressure in the alveoli equilibrates with atmospheric pressure. Expiration is relatively passive at rest, but at higher levels of ventilation some expiratory muscles do contribute to the expiratory process.

Muscle groups enabling ventilation: The combined efforts of muscles of the chest wall, principally the diaphragm, expand the volume within the thoracic cavity, leading to inspiration. Of these, the diaphragm is the primary muscle of ventilation.

The diaphragm (Figure 8.1) is a dome-shaped muscle that separates the thoracic from the abdominal cavity. It is a thin, sheet-like muscle that originates on the lower rib cage (costal diaphragm) and lumbocostal spine (crural diaphragm) and inserts on the central tendon.

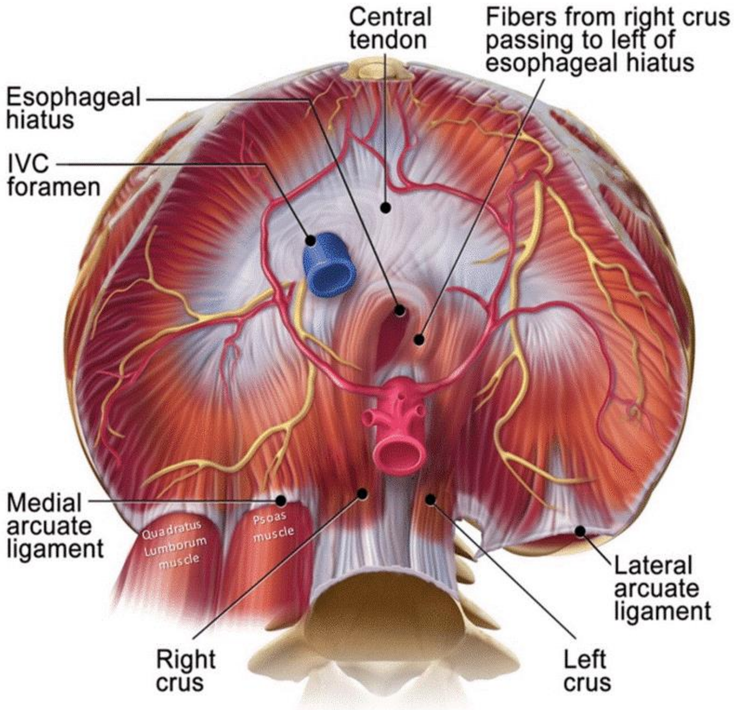


Figure 8.1. Diaphragm Anatomy

The diaphragm can be considered as a cylinder capped by a dome (Figure 8.2). During inspiration the muscle fibers of the diaphragm shorten, but the dome of the diaphragm does not change shape.

Movement of diaphragm acts to increase thoracic volume by several mechanisms. During contraction, the diaphragm is directed downwards with a piston like action. As the diaphragm descends down from the thoracic cavity and into the abdominal cavity thoracic volume concomitantly increases. Due to its insertion on the lower ribs, the diaphragm imposes a cranially-directed force on the lower rib cage, lifting the ribs and rotating them laterally.

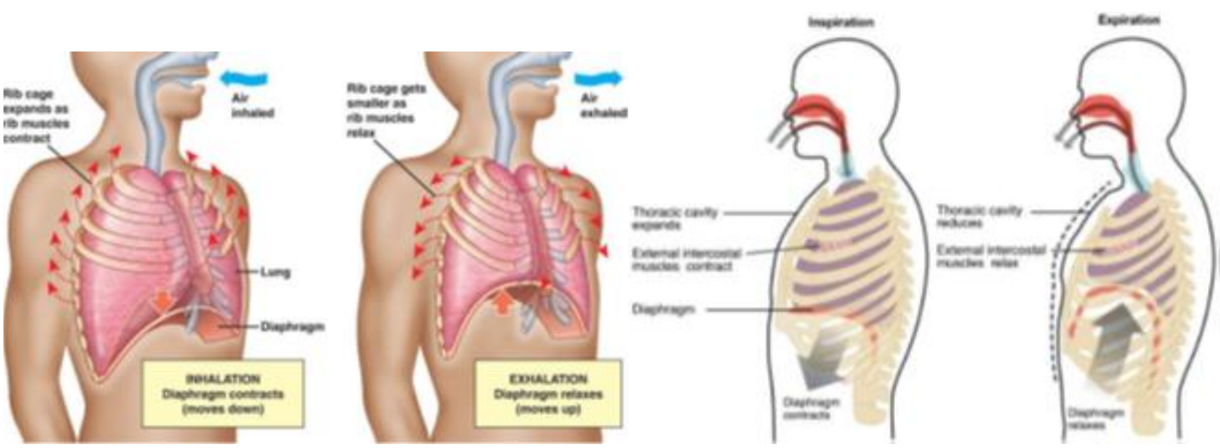


Figure 8.2. Inspiration and Expiration Muscular Mechanics

In addition to the diaphragm, the intercostal muscle group contributes to inspiratory portion of ventilation. The intercostal muscles can be divided into three groups: the parasternal intercostals, and the external and internal intercostals.

The parasternal intercostals originate on the lower rib, adjacent to the sternum, and then insert onto both the sternum and the rib directly above. The parasternal intercostals have an inspiratory mechanical action. The external and internal intercostals are located more laterally between the ribs. Due to their fiber orientation and pattern of activation during breathing, the external intercostals also tend to produce an inspiratory action. In addition to the above muscles, several muscles in the neck (scalens, sternocleidomastoid) elevate the sternum and upper two ribs during deep inspiration, aiding in the inspiratory action on the thorax. During inspiration, enlargement of the upper rib cage is due to actions of the neck and intercostal muscles, but enlargement of the lower rib cage is due to the actions of the diaphragm and intercostal muscles.

While the parasternal and external intercostals are concerned with inspiration, the internal intercostals tend to produce an expiratory action on the rib cage during quiet breathing (Figure 8.3). An additional rib cage muscle, the triangularis sterni, originates on the inner aspect of the sternum and inserts on the ribs adjacent to the sternum and also has an expiratory action on the rib cage.

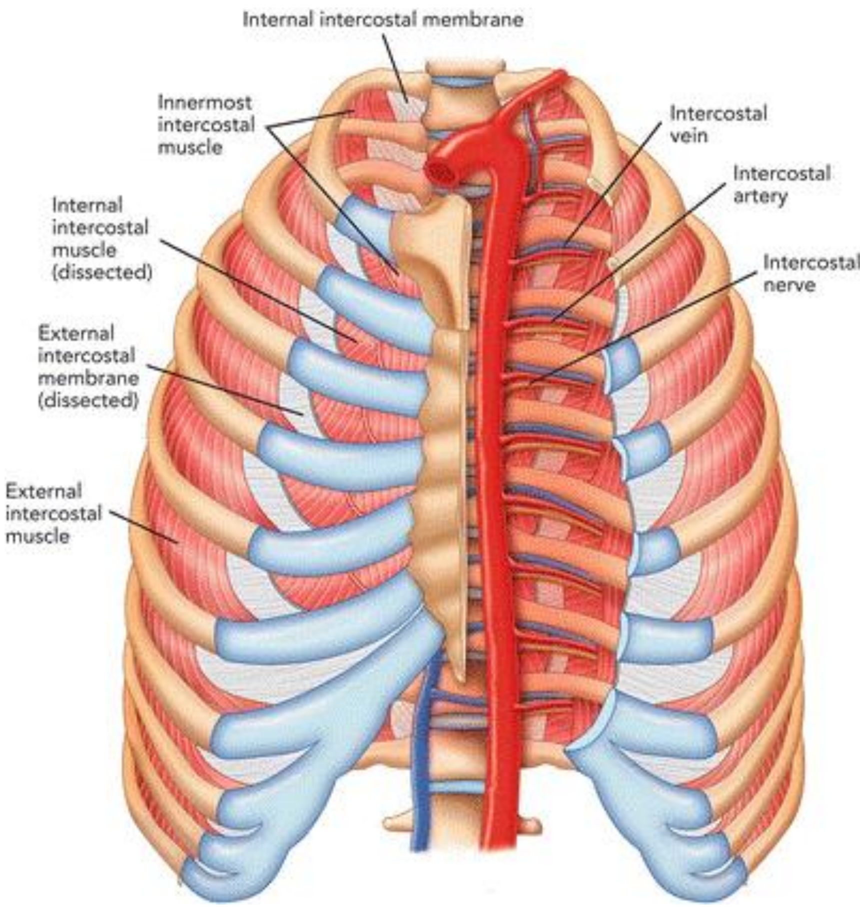


Figure 8.3. Intercostal Muscles

Additionally, four expiratory muscles are located in the anterolateral abdominal wall: the transversus abdominis, internal and external obliques, and rectus abdominis. They reduce thoracic size by increasing abdominal pressure which moves the diaphragm back into the thorax cavity. Those movements, in conjunction with their action of pulling down on the rib cage, decrease thoracic volume to facilitate exhalation.

The diaphragm, parasternal intercostal, and external intercostal muscles are the most consistently active during resting breathing in humans. Consequently, these are considered to be the primary ventilatory muscles while the others can be considered as accessory ventilatory muscles. Their activation occurs when ventilatory demands increase, for example, with exercise. Respiratory muscle fatigue and reductions in ventilation are reported during use of inspiratory and expiratory positive pressure.

These breathing muscles enable ventilation through the conducting airways (the nose, mouth, pharynx, larynx, trachea, bronchi, and bronchioles) before entering the alveoli.

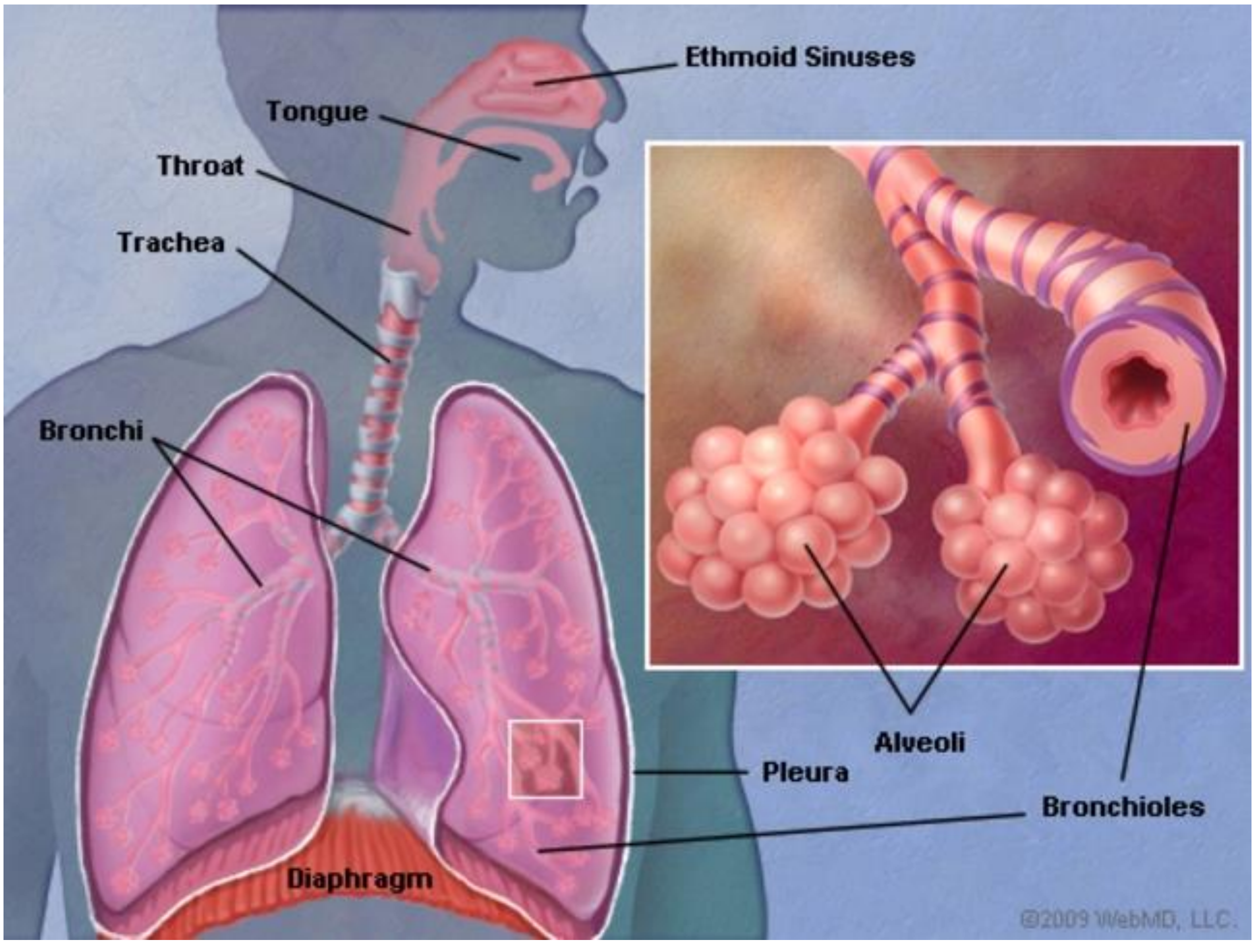


Figure 8.4. Pulmonary (Lung) Anatomy

<u>Dead Space</u>: Air that does not undergo gas exchange is referred to as physiologic dead space. The total dead space volume is made up of alveolar and anatomical dead space. Alveolar dead space is the gas that remains in the individual air sacs or alveoli to keep the alveoli open. Anatomic dead space refers to airs in the conducting passageways of the respiratory system, including the nose, mouth, pharynx, larynx, trachea and airways up to the terminal bronchioles. O_2 and carbon dioxide do not significantly exchange between gas and blood while in the conducting airways. This physiologic dead space, or residual volume, is typically approximately 150 mL in an average adult.

Dead space will increase with use of aircrew equipment, the largest contribution coming from the mask. Mechanical dead space (e.g., in a mask) can become rebreathed air that increases in carbon dioxide if not completely replaced with each breath volume delivered to the mask. This will increase the content of CO_2 to the lungs. Mechanical dead space can also become additional retained (unexhaled) air with excessive expiratory pressure. This dead space does not participate in gas exchange, and can lead to increased alveolar CO_2. Increased physiologic dead space (e.g., atelectasis or retained air) limits gas exchange and can contribute to hyperinflation. Furthermore, following a rapid decompression event, dead space volume will cause an immediate reduction in available inspired O_2, potentially leading to hypoxia. As a principle, added dead space volume by aircrew equipment should be no more than 150 mL

Pulmonary Volumes are the volume of air present in the lungs and airways at different phases of the respiratory cycle.

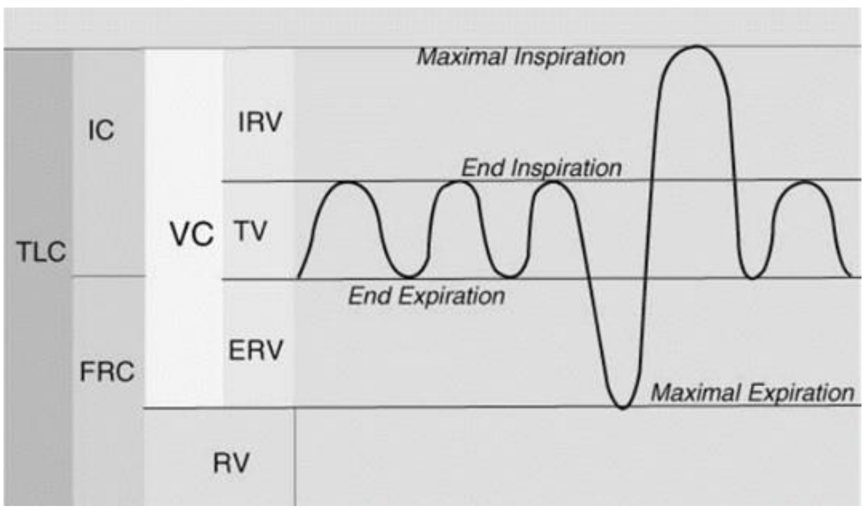


Figure 8.5. Pulmonary Volumes

The volume of air that is moved with each breath is defined as the Tidal Volume (TV). At rest TV is approximately 0.5L or 500 mL, which can increase greatly with exertion. Resting lung volumes are defined by the relationship between the inward elastic pull of the lung tissue and the outward expansile force of the chest wall. When relaxed, the lung has a volume of air within defined as Functional Residual Capacity (FRC). This is made up of the Expiratory Residual Volume (ERV) and Residual Volume. The expiratory reserve volume (ERV) is the additional air that can be forcibly exhaled after the expiration of a normal TV. The residual volume (RV) is made up of physiological dead space. This residual volume is typically fixed for an individual in the range of 1.2L or 1200mL. Active inhalation will expand the lungs to a volume greater than FRC, and passive exhalation will return lungs to FRC.

Vital capacity (VC) is the maximum volume of air that can be moved in the lungs – a maximum effort inhalation followed by a maximum effort exhalation. Typically, VC is on the order of 5L or 5000mL. Total lung capacity (TLC) is the sum of VC and RV. Inspiratory capacity (IC) is the maximum volume of inhale from FRC. Inspiratory reserve (IRV) and expiratory reserve (ERV) represent the volumes of air that can be moved at end inspiration and end exhalation, respectively.

Numerous features of the breathing gas system and aircrew equipment can serve, often synergistically, to adversely affect resting lung volumes. If expansion of the chest wall is limited, as is the case when strapped in to the aircraft, this will limit lung volumes including VC. By decreasing the natural outward pull of the chest, or outright resisting chest expansion, more inspiratory force is required for breathing. If lung elasticity is also increased, as is the case with unequal ventilation due to atelectasis or collapse of alveoli or segments of alveoli, this will further increase the effort of breathing. Chest wall restriction also limits the body's natural defense mechanisms against atelectasis.

<u>Ventilation Rates</u>: Pulmonary ventilation is the volume of gas per unit time entering the lungs, often defined as MV in units of L/min. Alveolar ventilation is the volume of gas per unit time that functions in for gas exchange, accounting for dead space. The alveolar ventilation rate (AVR) is the expression of this functional exchange of air, defined and illustrated below:

AVR	=	frequency	X	(TV – dead space)
(ml/min)		(breaths/min)		(ml/breath)

The normal respiratory rate at rest is variable between individuals and within a given individual. Normal rates for the pilots range from 12 to 18 breaths per minute. The breath structure at rest characteristically has an inspiration to exhalation time ratio of 1:2 to 1:3, with more time spent in exhalation – a passive process. This will increase toward 1:1 inhalation/exhalation under exertion. Safety pressure also changes the I/E ratio closer to 1:1 due to higher pressures causing exhalation to become more active instead of passive. During anti-G straining maneuvers, breath structure is radically different, notable for rapid, maximum exhalation and inhalation efforts in a very short period of time. Flow limitations, pressure variations and dyssynchrony in demand/supply will alter the breath structure forcing the pilot to attempt to adapt. This will be explained in detail.

Flow of gas across the capillary wall into the blood stream within individual alveoli is influence by the partial pressures of gasses in the alveoli. An effective breathing gas system would be tailored to maintain the O_2 content within the alveoli at physiological levels (about 104 mmHg) while minimizing the toxicity associated with high inspired O_2. The general alveolar gas equation describes the partial pressure of O_2 within the alveoli as a function of the inspired O_2 concentration:

$$P_AO_2 = P_IO_2 - P_ACO_2 * (FIO2 + [\ 1 - F_IO_2\ ] / R\ )$$

P_AO_2 = partial pressure of oxygen in the alveoli, normally 100 mmHg

P_ACO_2 = partial pressure of carbon dioxide

F_IO_2 = fractional inspired oxygen content

R = respiratory quotient, approximately 0.8 in the healthy aviator

Alveolar ventilation rate is negatively influenced by decreased TV and increased dead space. The body has many mechanisms to alter ventilation in response to fluctuations in gas exchange and composition in the blood stream. In response to increased PCO_2, the body will increase ventilation in a linear fashion. For every 1 mmHg increase in PCO_2 above normal (range 35 to 45 mmHg), ventilation will increase by 2 to 3 L/min. Ventilation will increase first elevating the TV and then by raising the respiratory rate. In an otherwise healthy adult, this drive will increase to a point past which central respiration fails, usually in the arterial range of 60 to 80 mmHg PCO_2. The ventilatory response to high PCO_2 is increased in the presence of hypoxia. The ventilatory response to hypoxia is based on Hemoglobin saturation and the provision of adequate blood flow to the lungs. Compensation to hypoxia occurs when the O_2 saturation is below about 95-96% or a drop in arterial O_2 contraction of 10-20 mmHg. This is done by various combinations of increased lung volume and respiratory rate. Maximal compensation is reached at an arterial O_2 pressure of 50 to 60 mmHg.

Gas exchange at the alveoli is connected to capillaries and is influenced by and has impacts on the cardiovascular system. This ratio of ventilation (V) of the lung to perfusion with blood (Q) is referred to as ventilation-perfusion ratio or V/Q. It is normal for the upright lung under the force of gravity to have more blood flow to the lower regions of the lung, and lesser blood flow near the apices. These regional differences are physiologic. Conditions which alter local ventilation or perfusion will adversely impact the function of the lung and the efficiency of respiration.

Airway resistance: which limits flow rates of gas into or out of the lung, is generated by aerodynamic forces of air movement within the lung. It is principally a function of airway diameter. Airway resistance is optimized at normal, resting FRC. Under conditions of increased airway resistance, the body will slow respiratory rates to provide more efficient respiration. It will be increased by changes in lung volumes and numerous additional conditions present in the breathing gas system of the F-35, including high O_2 concentrations and the atelectasis that will ensue. Any increased airway resistance is undesirable. Impedance to expiration will reduce average and peak flow rates, prolong exhalation and, over time, lead to lung hyperinflation.

Cardiac Output: Breath dynamics, lung volumes, and ventilation pressures are intrinsically linked with cardiac output and vascular function. This is particularly of consequence in the demand regulator system currently In normal, resting physiology, active inhalation occurs with a decrease in intrathoracic pressure, which helps draw low pressure venous blood into the right heart, increasing right heart output and filling the pulmonary arteries and capillaries. This leads to an intra-breath increase in blood volume in the pulmonary circulation, facilitating gas exchange. During exhalation, intrathoracic pressure will increase, helping to push oxygenated blood back through the left heart and into systemic circulation. Output is limited by net blood flow from the right side of the heart through the pulmonary circulation, which may be reduced with excessive airway pressures. For reference, the right atrial pressure normally is approximately 2 – 6 mmHg and normal right pulmonary artery pressure during contraction (systole) is 15 – 25 mmHg. Positive airway pressures which exceed the low pressure venous and pulmonary circulatory systems will impact cardiac output.

Flight Related Pathophysiology

Atelectasis is the term applied to describe collapse of alveoli, the functional end-units of the lung. Atelectasis is another lung decrease in ventilation that also affects circulation. There are a multitude of medical causes of atelectasis, but to the healthy aviator, the etiologies of high prevalence and concern are acceleration and absorption atelectasis. Atelectasis of any kind will result in reduced lung function and can cause symptoms of chest pain, irritation, or cough. Normally, the pressure of nitrogen within the alveolus will maintain patency through the breath cycle. If nitrogen is removed from the alveolus, as is the case when breathing concentrated O_2, the body will rapidly absorb available O_2 within the alveolus. This will decrease the pressure of gas within the alveolus and potentially leading to collapse. There is a critical point at which inspired oxygenated gas entering the alveolus is balanced by O_2 uptake by the bloodstream, with atelectasis becoming increasingly likely with inhaled gasses composed of 60% or more of concentrated O_2. Collapsed alveoli will cease to participate in gas exchange until reopened, perhaps by coughing or deep breathing. However, even after being reopened by such a maneuver, these alveoli will be unstable and more likely to collapse again. Referred to as denitrogenation absorption atelectasis, this can cause significant and cumulative changes in lung ventilation and perfusion over time.

Acceleration Atelectasis: Under vertical acceleration forces, + G, there will be regional changes in blood flow in the lungs which will lead to the formation of acceleration atelectasis. Under sustained + G_z, the lower regions of the lung segments will see increased blood flow, and the apices will see progressive decreased flow. At + 5 G_z and greater, the upper half of the lung will effectively be nonperfused. This nonperfused lung is effectively ventilated dead space. Conversely, the lower regions of the lung will receive increased blood flow to the point of becoming engorged and collapsed, having then no ventilation, but high perfusion. This can result in shunting of deoxygenated blood to mix with oxygenated blood in circulation, lowering the O_2 content in arterial circulation. This can also lead to the formation of atelectasis in the lower portions of the lung – portions which normally play a more significant role in ventilation due to higher perfusion.

Acceleration atelectasis will begin to occur by + 3 G_z, and be prominent from + 5 to + 9 G_z. Use of anti-G suits will exacerbate this exposure, causing restriction of the diaphragm and fall in FRC. Sustained, this can result in a shunt of deoxygenated blood on the order of 20 to 25% of total blood flow. Acceleration atelectasis will be exacerbated with inspiration of high O_2 concentrations. Atelectasis will reduce the functional capacity of the lung, limiting and whenever feasible measures should be taken to minimize the causal forces.

Hyperoxia: Inspiration of higher O_2 concentration, necessary with increases in altitude with less O_2, has a multitude of undesirable adverse effects as concentrations increase, including atelectasis. O_2-enriched air can lead to the production of reactive O_2 species which can directly cause inflammation, alveolar damage, and respiratory distress, concurrent with and in addition to atelectasis, as previously discussed.

O_2-induced changes in neurovascular tone: A topic of ongoing interest, the inhalation of high concentrations of O_2 has been found to cause regional blood flow changes in the brain and changes in brain function. Damato et al. demonstrated reduced blood flow by Magnetric Resonance Imaging, with some preservation of cognitive function. (Ref Section F-35 Hyperoxia). Although memory may not be affected, some areas of reasoning and judgement may be affected. These vascular changes are under investigation and may prove insightful in delineating the pathophysiology of Hyperoxic cerebrovascular changes and cognition.

Rapidly Oscillating Hyperoxic Concentrations: During the T-6 Safety Investigation Board for unexplained PEs, it was determined that fluctuating O_2 can cause hypoxic like symptomology (19AF OBOGS Summit Jun 2019 After Action Report and report of Safety Investigation Board, Jun 2019, Randolph AFB.) While there are currently no formal studies on humans or pilots to reference, the medical literature on animals does support this. Boehme et al. demonstrated that oscillating O_2 induced release of proinflammatory cytokines in the lung, followed by onset of inflammation.

Oscillation Pressure Effect on Surfactant: Surfactant is the coating that helps to prevent alveolar collapse. Pressure oscillations facilitate atelectasis formation by displacing surfactant. In combination with decreased nitrogen and/or acceleration, this further increases the amount of atelectasis in the lungs. Higher pressure oscillations can also cause barotrauma to the airways and alveoli. High pressure oscillations potentiate lung damage through a variety of mechanisms. High pressure oscillations cause mechanical stress and strain within the lungs, as the mechanical force applied to the pulmonary epithelium lining the airway and the alveoli initiates a resultant inflammatory response within the lungs. An inflammatory response can spread to other organs causing secondary barotrauma.

Asynchrony: is a pervasive problem in mechanical ventilation of critical patients, but it also is a contributing factor in aircrew breathing systems. One form of asynchrony (dyssynchrony) involves timing of mechanical triggering of the system to the pilot's individual breaths. Asynchrony is defined as the triggering or cycling of a breath that either leads or lags the pilot's inspiratory effort. Regarding the size of a breath, asynchrony means the inspiratory flow or TV does not match the pilot's demand (too much/little, too early/late). Asynchrony will lead to increased work of breathing, excessive fatigue of respiratory muscles, and non-specific respiratory discomfort. Volume and flow mismatches can cause micro-trauma in the form of barotrauma due to alveolar over distention even if the pressures are not excessive in the traditional sense of high PIP/PEEP. Asynchrony is a subtle problem for which patients have no way to perceive or communicate its presence directly. (Ref sec -Asynchrony)

Inspiratory Over Pressure: In the F-35 electronic safety pressure regulator, we have seen that the response is not proportional to the demand from the pilot and varies at the beginning, middle and end of the response. High safety pressure in combination with sudden and unexpected inhalation flow towards the end of inhalation can lead to inspiratory overpressure. With even small amounts of safety pressure, inhalation will become more passive while exhalation becomes an active process. This inhalation/exhalation reversal will change chest wall and lung dynamics, usually resulting in expansion of the lung and increase in FRC. Exhalation becomes prolonged, and indicative of increased effort needed to breathe out against pressure. The work of breathing will increase, and even the small safety pressures utilized in modern demand regulator systems can contribute to hyperinflation and fatigue over time. Higher levels of positive pressure, particularly above the intrapleural pressure of -4 mmHg, can have adverse consequences. Trained individuals can tolerate pressure breathing up to 30 mmHg for very short periods, to compensate with a high altitude cabin pressure decompression. In the high G_z regime, combined with G-straining maneuvers, a pressure of 60-90 mmHg can be tolerated in short durations. If left for longer it will lead to hyperinflation, hypoventilation, fatigue, and respiratory failure. Positive pressures of 4-10 cm H2O can be well tolerated, but require a constant, uninterrupted flow with no oscillations. Higher pressures to 20 cm H_2O are also tolerated, but do result in higher rates of dry mucous membranes and nose bleeds. In a system with increased peak pressures or flow, the addition of continuous airway pressures serves to worsen hyperinflation. Hyperinflation due to asynchrony results in insufficient exhalation time preventing the respiratory system from returning to its normal resting equilibrium volume between breaths. So in using safety pressure, it must use in the light of normal inspiratory flow rates, peak pressures, a synchronized breathing system, and normal tidal volumes.

Excessive expiratory pressure: This has physiological consequences and can cause perfusion problems. Normal respiratory dynamics function as a negative pressure system during inhalation. As described previously, the diaphragm descends and produces a negative pressure in the airways that draws air for gas exchange in. This same negative intrathoracic pressure decreases the right atrial pressure and draws blood from the inferior vena cava and increases venous return to the heart. An increased airway exhalation pressure is reflected in the airways and alveoli. That negative pressure in turn is transmitted to the thoracic cavity and decreases the negative pressures from the diaphragm (creating a positive pressure). This increases right atrial pressure, decreasing venous return. This affects the pulmonary flow and decreases overall heart volume. This has a doubling effect of decreasing cardiac output as well as less effective cardiac function. This can result in overall drop in mean arterial pressure, which extrapolated to a fighter aircraft pilot can result in brain hypoxia.

Hyperinflation: Inappropriate and excessive exhalation pressures will lead to dynamic hyperinflation. This condition is the increase in lung volume (over inflation) that occurs whenever insufficient exhalation time prevents the respiratory system from returning to its normal resting end-expiratory equilibrium volume between breath cycles. This results in trapped air, inability of the pilot to initiate a breath, and an increased work of breathing. Hyperinflation also results in limited inhalation volumes, as the excessive exhalation volume is not displaced. This increases the physiologic dead space. In the case of dynamic expiratory hyperinflation, volumes of both inspiration and exhalation are decreased, TV is diminished and a state of hypoventilation results. Persistent breathing dysfunction (oscillations, lung over-inflation, and forceful exhalation) can cause long term changes to pulmonary function.

Barotrauma: If peak inspiratory pressure is too high, the compensatory reaction is to limit TV so as to prevent excessive pressure on the airways and alveolus. An excess pressure can cause over distention of the alveoli to the point that they lose structural integrity and collapse. High alveolar pressures can be due to excessive TV, gas trapping, excessively high expiratory pressures or low compliance ("stiff lungs" or lung tissue that has limited elasticity). This may result in hypoventilation of the patient and hypoxia. Chronically high airway pressure may cause micro-barotrauma to the alveoli and accumulates over time.

Discussion

The above framework can serve as a brief guide to develop an understanding of some of the vulnerabilities of the respiratory system that may be affected in the F-35. Many of the physiological properties of the lung will vary between breaths or within an individual breath to maintain the proper balance of O_2 and carbon dioxide within the blood. This highly tuned, highly responsive system will respond consciously and subconsciously to external forces. The body will make efforts, consciously or subconsciously, to attempt to restore alveolar ventilation. If there are external forces at work limiting this physiological response, there may be undesirable symptoms of dyspnea, nausea, cough, or worse. If the human's physiologic reserve is depleted, and, without awareness, the pilot may acutely become incapacitated. Within the turbulent nature of high-performance aircraft, small, consistent perturbations can have cumulative effects, even if the breathing gas systems are functioning within current design specifications. The human system is constantly responsive to pressure, volume and time, and so any fluctuation will result in changes that affect the function of the entire system.

8.2 Analysis

The data from the F-35 display patterns of mismatch and dyssynchrony between the pilot and breathing gas system. These impacts are pervasive and can cause undesirable respiratory changes which align with pilot reports and interviews.

In-flight investigations into respiratory physiology and pathophysiology are nascent, but the patterns observed thus far are cause for concern.

- "And so there was this, kind of, general kind of breathing technique that I learned, like I said, I guess it was more subconscious than I initially said just then. Where it was kind of: initiate the breath, then breathe while I have flow, and then you kind of have to exhale a little bit more forcibly, and that sort of stops and resets the valves, and then you can exhale and finish the exhale process. It definitely takes more attention, whether it subconscious or conscious, to breathe in the F 35 than it does in any of the other airplanes that I've flown, including ones I did fly, and I'm trying to remember right, I did fly a couple of other airplanes; F-15s with the OBOGS and a flew an F-18 with the OBOGS, and those I don't remember having any need to adapt my breathing like I had to in the F 35."

Pulmonary consequences: Loss of minute ventilation is reflective of an inability of the pilot to adequately adapt to the breathing environment. Many of the patterns in the data, including dyssynchrony, increased impedance to airflow, and undesired dynamic pulmonary changes, can interact synergistically to reduce minute ventilation.

Dyssynchrony is the product of mismatch between pilot demand and supplied flow. The data demonstrate that pilot demand and airflow supply are disjointed. Early in the breath demand exceeds supply, whereas later at the end of the breath by supply exceeds demand. When supply exceeds demand at the end of a breath, this will result in an excess volume of air being forcibly delivered to the pilot, with a number of concerning effects. The data consistently demonstrates metrics of hysteresis and phase shift. Increasing time to 50% inhalational volume will physiologically result in reduction in tidal volumes, consistent with trends observed. Dyssynchrony is also facilitating dynamic hyperinflation of the lungs in conjunction with increased impedance to airflow.

Reduced Minute Ventilation: Starting with the TVs (Figure 8.6), the pilot in Aircraft 1 shows a 0.7L peak inhale TV, vs. 0.9L for Aircraft 2. This represents a significant reduction in TV, recalling that these TV measured include dead space ventilation. The reduction in TV in Aircraft 1 also thus reflects a decreased proportion of each breath which participates in alveolar ventilation – breathing is much less efficient in Aircraft 1 vs Aircraft 2.

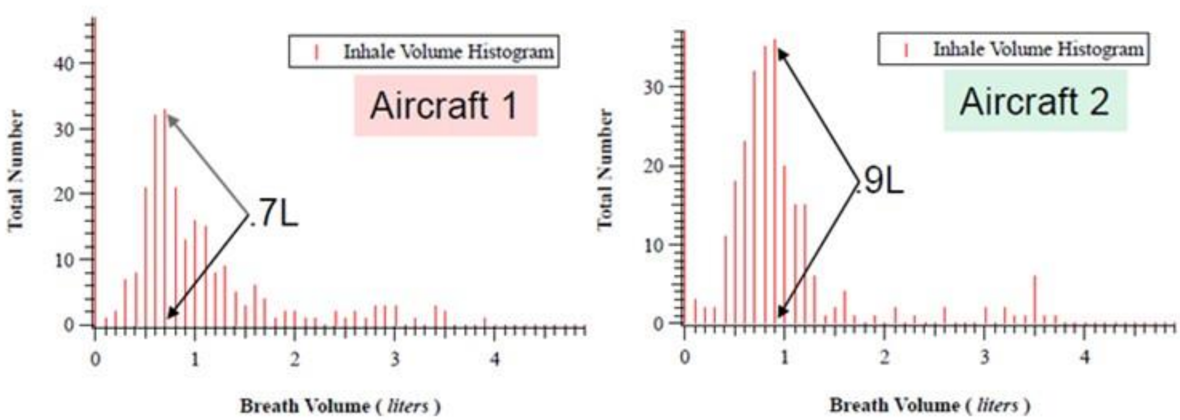


Figure 8.6. Reduced TV on Aircraft 1 compared to Aircraft 2

In addition to being 20% lower on Aircraft 1, the histogram shows a more variable and skewed distribution. Breathing is stochastic in nature, and the distributions analyzed in the F-18/F-15 during PBA flights are more normally distributed. The skew in the distribution away from a normal distribution indicates an influence on the normal physiological distribution of breaths, which is larger in Aircraft 1. Evidence indicates that this can be imperceptible or barely perceptible to pilots in flight, despite the significance. Compensation occurs readily provided the pilot does not require an increase in TV to contend with an increased metabolic demand. Many perceptions related to in flight compensation may be manifested post flight with fatigue and malaise due to the increased work of breathing.

The inhale breath time distributions are shifted longer on Aircraft 1 by 20%. This increased inhale breath time is a physiological adaptation to undesired and problematic flow restriction. It reflects also a disruption of the natural breath structure, with increased inhale/exhale time. The body naturally will try to preserve volume by slowing down the respiratory rate and increasing breath to breath volume, provided the restriction is not variable. This clearly shows variable restriction and asynchronous patterns.

Another indicator of restriction during inhalation is the reduction in Inspiratory Capacity (IC) indicated by a reduction in maximum achievable TV. Both the peak flow rate and resulting maximum TV are lower on Aircraft 1 by 15%. Aircraft 1 is limited to 3.4L compared to 4.0L on Aircraft 2. Both reflect a decreased TV compared to a healthy aviator, who would be expected to achieve approximately 5L. Some degree of loss is known to occur with the added weight and restriction of flight equipment. However, if this was a volume restriction was chiefly due to aircrew flight equipment such as flight jacket, seat harness, or other physical restrictions to actual expansion of the chest itself, there should be minimal difference as the configuration worn was identical in both cases.

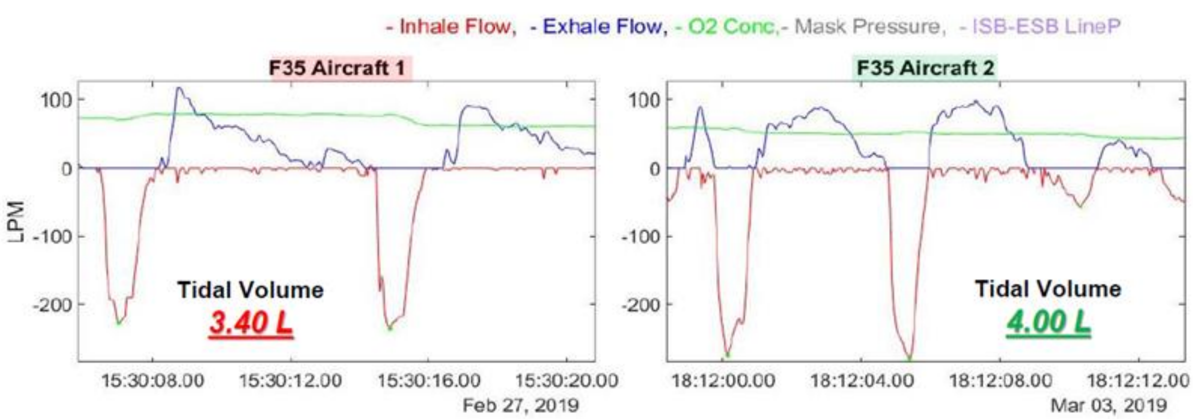


Figure 8.7. Reduced TV during Maximum Inhale on Aircraft 1 compared to Aircraft 2

When the G-suit was disconnected on Aircraft 1, the maximum TV increased to 3.7L, which is inconsistent with purely external chest wall restriction. Also, chest wall restriction, which causes decreased breath volumes, would be expected to elicit an increased breath rate to maintain adequate ventilation. However, longer duration inhalation reflects the expected compensation for a flow restriction, and we can visibly observe it here again with Aircraft 1 taking approximately 20% longer to get 15% less air (Figure 8.7).

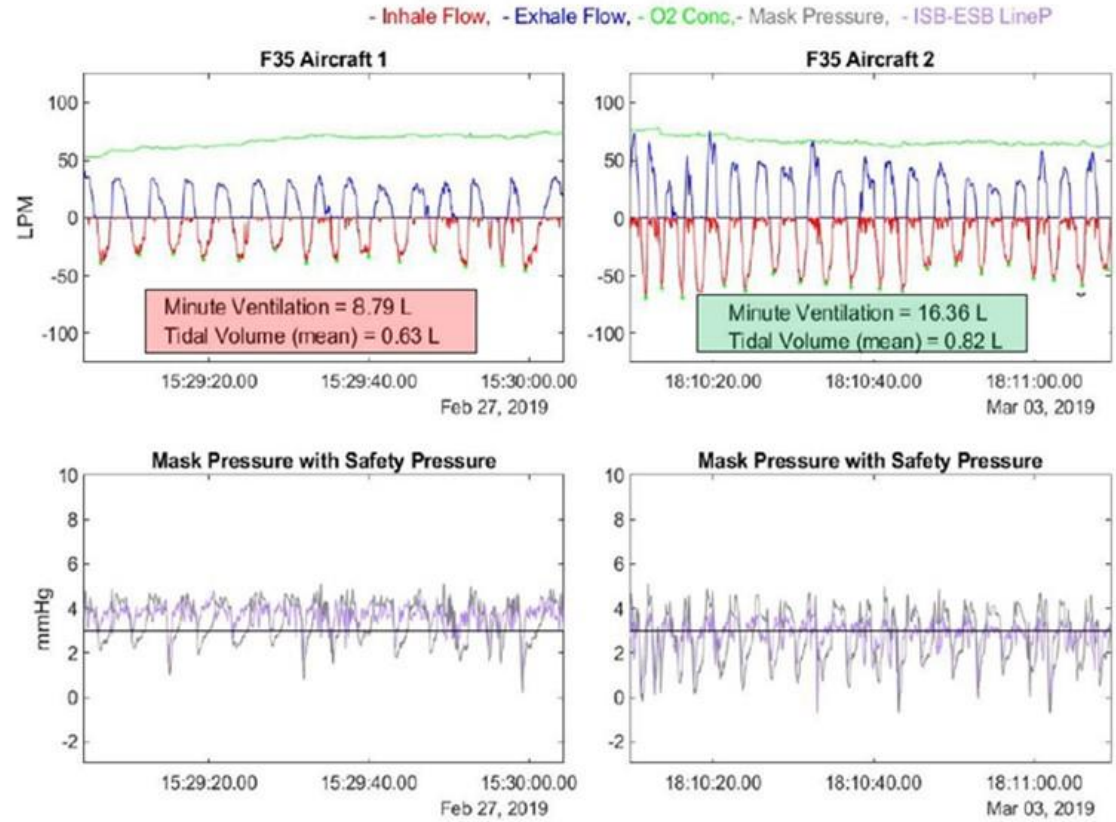


Figure 8.8. Normal Relaxed Breathing for Aircraft 1 and Aircraft 2

Physiologically, the lower TVs and longer breath times in Aircraft 1 result in reduced MV (Figure 7.1). Aircraft 1 had TV's of .63L and MV of 8.79L compared to Aircraft 2 which had TV's of .82L and MV of 16.36L. These data were collected during periods of relaxed breathing without exertion, and it would be highly irregular to have such grossly different MV in the absence of medical condition. The pilot in Aircraft 1 received approximately 50% less air with TV's 25% lower. On Aircraft 1, the inhale and exhale flows are much less stochastic than on Aircraft 2, further indicative of flow limiting effects. Analysis of mask pressure reveals a number of concerning trends which show pathological changes in pulmonary function and all but certain impact to cardiac function. Average mask pressure swings for each breath are lower on Aircraft 1. In Segment 1 (Figure 8.8), Aircraft 2 has mask pressure which drop down to 0 to 1 mmHg regularly, whereas Aircraft 1 rarely drops below 2 mmHg. These reduced pressure swings are also seen in (Figure 8.8) in comparison to MIL-STD 3050. These lower mask pressure excursions are a concerning finding, suggesting inadequate compensation of the human to flow limitations and reduced TV.

Alveolar overdistension: Overdistention is likely occurring as a result of pressure demand/flow mismatch. The data demonstrates that pilot demand and airflow supply are disjointed. Early in the breath demand exceeds supply, whereas later at the end of the breath by supply exceeds demand. When supply exceeds demand at the end of a breath, this will result in an excess volume of air being almost forcibly delivered to the pilot, with a number of concerning effects. This undesired and excess airflow will be directed to more patent and highly ventilated regions of the lung, with the possible end result of regional alveolar over distention forcible exhalation is initiated during peak regulator flow, as is frequently the case, this may further increase transpulmonary pressures and stress on the alveoli. On the microscopic level, the alveolar over distension will lead to inflammation, disrupted blood flow, collapse and loss of function. Alveoli that have been over distended may be subsequently stretched open on successive breaths; they will be unstable and prone to collapse again. The cyclical atelectasis that results will lead to further injury and the shear forces will be transmitted locally, causing neighboring alveoli to also collapse. The end result is somewhat of a 'micro-tear' in lung tissue, with cumulative progressive injury, inflammation and loss of tissue function, which will continue as long as the mask and regulator are on. (Ref sec– Barotrauma)

The pathological effects of breathing gas system hysteresis or dyssynchrony will be most pronounced during periods of high metabolic demand with large lung volumes and rapid breath rates, but can also impact function during quiet breathing due to the disproportionately large magnitude of the dyssynchrony compared to the small pressures used at rest. The body may attempt to compensate for this process with slowed respiration with feedback from lung stretch receptors via the Hering-Breuer reflex, but this will pose yet another risk for hypoventilation. Once activated, the receptors send signals to the inspiratory area in the medulla and brain stem. In response, the inspiratory area is suppressed directly and inhalation is inhibited allowing expiration to occur. With constant pressure against the chest wall and airways this can result in slowing of respiration.

Circulatory consequences: Pulmonary circulation may be affected by the demand regulator safety pressure system, with downstream changes in cardiac output and systemic vascular function. These changes can be classified by their principle etiology: effects of safety pressure, pressure and flow hysteresis, and pressure oscillations. Safety pressure in combination with pressure alterations and flow restrictions, may increase pressure within alveoli, reducing capillary perfusion pressure, although this potential effect has not been demonstrated to be physiologically relevant. The effects of low safety pressure (3 mmHg) alone are small, but are additive with other increases or fluctuations in inspired gas pressures. Higher positive airway pressures will increase pulmonary artery pressure and right heart loading, decreasing right heart output and exacerbating any underlying shunting or V/Q mismatch.

Pressure oscillations alter pulmonary blood flow. These oscillations can be transmitted to alveoli, and the resultant physiological effects depend on a host of factors. These factors include the frequency and magnitude of the oscillations, the time during breath when the oscillations occur, and the current physiologic state of the lung (lung volumes, atelectasis, etc.). If the magnitude of the oscillations are large, they may be additive with safety pressure to cause pathological reductions in pulmonary capillary perfusion, increase right heart strain and worsening any existing V/Q mismatch. If the oscillations occur in the presence of regulator hysteresis, the effects may be magnified, with significant changes in regional blood flow. Airway and thoracic pressures above venous or right heart pressures will be transmitted to the systemic venous system and cerebral veins, limiting flow and reducing perfusion. High thoracic pressures will also trigger the baroreceptors in the aortic arch with reflexive slowing of heart rate and reducing cardiac output. Reduced cardiac output, in conjunction with reduced cerebral perfusion pressures and coexisting reflexive hypoventilation are a recipe primed for hypoxic insult.

Mask Pressure Swings: Low mask pressures and lower swings in mask pressure are usually thought to denote a system that is performing as designed, but that is not necessarily true when a flow restriction is present. Conversely, elevated mask pressures and larger mask pressure swings are traditionally considered to denote a poorly performing system, but pilots do not perceive that those pressures as large or objectionable when the flow adequately responds in tune with large demands. In either of the previous cases, pilot perception of breathing performance may not correlate well with the magnitude of mask pressure. Rather, pilot perception of breathing dynamics appears to depend more upon receiving a flow commensurate with demand and without delay. Excessively high inspiratory and/expiratory pressures will cause a commensurate decrease in TVs. The higher the peak pressures, the more the TVs will be restricted to prevent barotrauma. However, fast oscillations as seen in the data can cause barotrauma before reflexes can protect against excessive pressures. At higher metabolic demands the protective restriction on TV will result in hypoxia over time.

It is likely that breath dynamics studied here have been significantly disrupted leading to increased ventilatory effort and lower demand mask pressures. Subconscious physiological adaptive measures to flow restriction are being exacerbated by the inefficient pulmonary dynamics of lower breath volumes. In other words, it is becoming clear that the pilot is fighting the machine to maintain normal homeostatic breathing, but in the case of Aircraft 1, the pilot is losing.

Oscillating Pressure consequences:

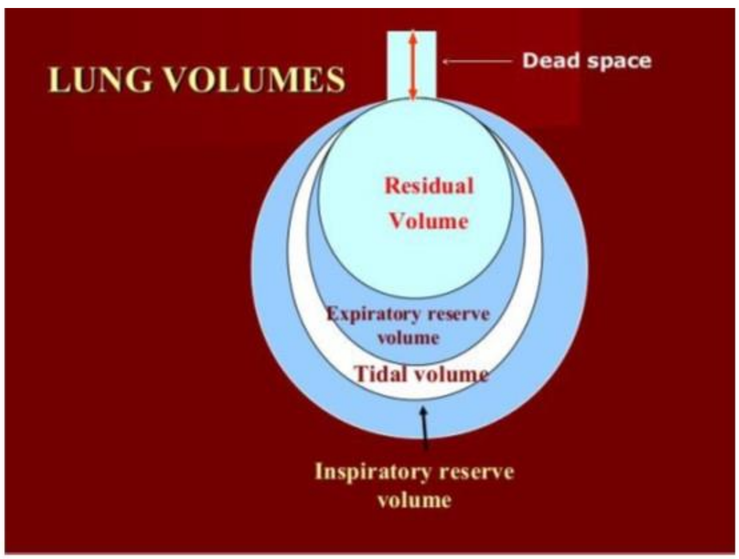
The level of flow restriction observed in Aircraft 1 by estimate appears to be moderate, as judged by the adaptive nature of the pilot's response and the lack of any reported resistance by the pilot. Trained aircrew, under most circumstances, would be unaware of the effects of increased resistance in the breathing gas system, highlighting the insidious nature of some of these issues. High flow resistances would be expected to cause slower, deeper breathing, which does not here appear to be the case. However, with any degree of flow or inhale resistance, the body will adapt to preserve MV, which, as above, is not the case. Again, it appears the pilot is fighting the machine, and the pilot is losing the battle.

Traditional thinking equates large drops in mask pressure as deleterious due to the increased work of breathing associated with large mask pressures. Traditionally, when a flow restriction was present, there was a corresponding increase in large negative pressures, which intuitively makes sense when breathing against an insufficient flow, such as a pinched off mask or straw. However, we do not see large negative mask pressures associated with Aircraft 1's flow restriction.

This combination of airflow restriction without a corresponding drop in mask pressure would be less prominent in a diluter demand breathing system, wherein flow response is proportional to the mask pressure demand and limited principally by regulator function. However, in this electronic safety pressure demand regulator, we have seen that the flow response is not in synchrony with the demand from the pilot. Rather, the supplied air varies at the beginning, middle and end of the inhalation demand. This hysteresis or dyssynchrony between the pilot and regulator can cause significant changes in respiratory dynamics, akin to trying to drink water from a faucet unpredictably varying its output from a dribble to high pressure stream. Air is not being adequately provided at the beginning of the breath, and too much is being delivered after demand ceases at the end of the breath. This is very different physiologically from a proportional or nearly linear response of demand for which the body is accustomed.

Physiologically, demand regulators with safety pressure create numerous issues and alter normal breathing dynamics. As previously discussed, at rest, inhalation is active and effort-driven, while exhalation is passive. With even small amounts of safety pressure, inhalation will become more passive while exhalation becomes an active process. This inhalation/exhalation reversal will change chest wall and lung dynamics, usually resulting in expansion of the lung and increase in FRC. Exhalation will become prolonged, indicative of the effort needed to breathe out against pressure. The work of breathing will increase, and even the small safety pressures utilized in modern demand regulator systems will lead to some degree of hyperinflation and fatigue over time. Higher levels of positive pressure, particularly above the intrapleural pressure of -4 mmHg, have adverse consequences although trained individuals can tolerate pressure breathing up to 30 mmHg for very short periods. This is usually associated with high G_z maneuvering or high altitude. If left unabated, this condition could lead to hyperinflation, hypoventilation, fatigue, and respiratory failure. (Ref sec - Aviation, Gz, and Hypoxia - AIN).

Hyperinflation: The following depictions are designed to illustrate the influences of over-pressurization leading to hyperinflation (i.e., continued increases in FRC). Reported instances of hyperinflation and increased FRC during the interviews correspond to the higher exhale pressures, decreased exhale flows, longer exhale times, saw tooth exhale pressure oscillations, and lower tidal volumes detailed in this report. Together these suggest the pathology of increased FRC occurs regularly with significant potential to cause harm. (Ref Sec – Barotrauma and Overpressure).



Tidal Volume (TV) – Air that moves into and out of the lungs with each breath (approximately 500 ml)
Inspiratory Reserve Volume (IRV) – Air that can be inspired beyond the tidal volume (2100–3200 ml)
Expiratory Reserve Volume (ERV) – Air that can be evacuated from the lungs after a tidal expiration (1000–1200 ml)
Residual Volume (RV) – Air left in the lungs after strenuous expiration (1200 ml); keeps alveoli inflated
Functional Residual Capacity (FRC) – Air left in the lungs after tidal expiration (RV + ERV)
Note: Only the TV is exchanged during each breath. None of the residual or reserve volumes are exchanged during each breath
Dead Space (Physiologic) – Alveolar RV plus all connecting airways that do not participate in air exchange

Figure 8.9. Normal Relaxed Breathing for Aircraft 1 and Aircraft 2

Figure 8.9 shows a normal alveolar volume distribution with the respective volumes labeled and defined. The individual alveolus is used to help visualize what happens to the lung volumes as a whole as residual volume increases (regional differences occur in the lungs, but the principle concept is the same).

There is a progression of effects due to excessive inhalation or exhalation pressures. During inspiratory overpressure, the natural compensation mechanism is decreased tidal volumes to prevent barotrauma (this compensation is not depicted) (Ref Sec - Overpressure)

Decreased tidal volume increases the airway and alveolar dead space by the amount of decreased tidal volume. A complete reduction in tidal volume to zero (breath hold) results in no barotrauma, but also no air exchange, as the entire lung becomes dead space.

In expiratory hyperinflation the residual volume expands as depicted in Figure 8.10. Normal residual volumes (left) become larger through a combination of higher inhale pressure (i.e., larger breath due to being stuffed with air) and higher exhale pressure (i.e., incomplete exhale due to reduced exhale flow or time). Passive exhale is no longer sufficient to return the lungs to their starting residual volume, and the residual volume gradually expands (middle). A complete expansion of the residual volume (right-like blowing up a balloon and tying off the end) results in no air exchange, as the entire alveolus becomes dead space. Natural compensation is for exhale to become active (requiring the use of muscles not normally engaged) with a significant increase in the work of exhaled breathing. The higher lung volumes associated with increased residual volume result in muscles having to work from a position of mechanical disadvantage, as they are already stretched out.

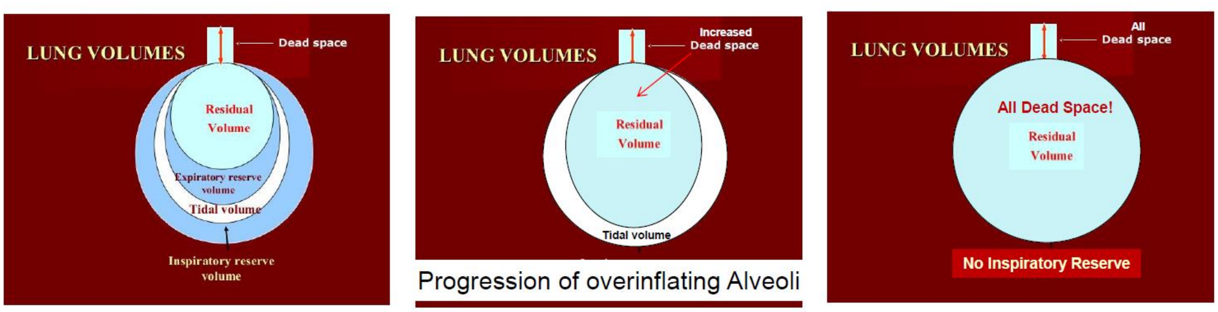


Figure 8.10. Normal Relaxed Breathing for Aircraft 1 and Aircraft 2

Persistent breathing dysfunction from breathing sequence disruptions (e.g., oscillations, restricted exhalation, and attenuated inhalation) can lead to decreased Inspiratory Capacity. Medical literature, multiple pilot reports, and data here indicating lower TVs all suggest F-35 pilots experience lung over-inflation and increased Functional Residual Volumes (Ref F-35 References).

Demand regulators also introduce dyssynchrony or asynchrony into the breathing system. As a general principle, demand regulators can be tuned for responsiveness or maximum flow. As previously discussed, however, breathing patterns in flight are highly variable and will simultaneously require instantaneous response and high flow rates, as is the case with anti-G straining maneuver breathing. Current regulations, based on pressure and flow rate specifications, do not account for the synchrony with human respiration or the hysteresis that they inherently produce. This is not unique to the F-35 and would apply to other aircraft using demand regulators.

<u>O_2 concentrations</u> varied by 20 to 40% over one-minute intervals in several occurrences. Large breaths produced a precipitous drop in breathing gas O_2 concentration. The concentration values were calculated from the regulator supply gas pressures measured at the ISB. There is currently no standard regarding magnitude or duration for O_2 concentration swings, and the values for the O_2 concentration fall within the current MIL-STD-3050 Figure 1 envelope (below), which only requires O_2 concentration to be above or below the minimum or maximum thresholds in order to prevent hypoxia (lower bound) and to prevent acceleration atelectasis (upper bound), depending on altitude. This legacy standard was conceived for liquid O_2 dilution style breathing systems (LOX) where O_2 concentrations did not vary significantly, nor did they oscillate continuously. The adsorption swing process in OBOGS makes the output inherently cyclical. The O_2 output can be stabilized, as is done on the F-15E MSOGS, by continuously producing sufficient near-100% O_2 and diluting to the appropriate schedule, much as LOX does, however this results in a larger and heavier system with excess O_2 production under most circumstances. There are no known studies showing that swings in O_2 concentration are safe.

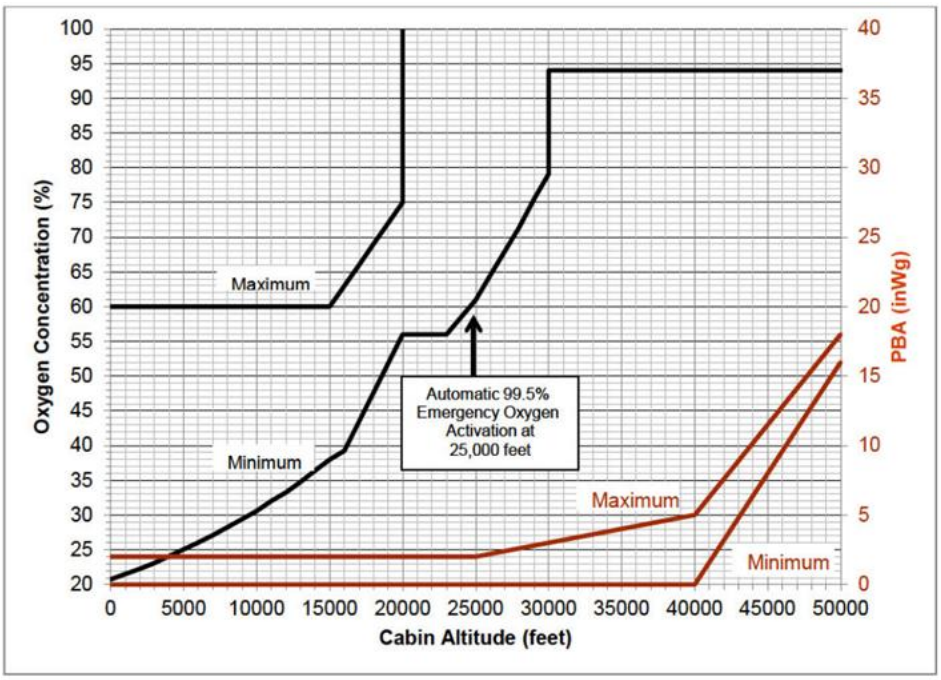


Figure 8.11. O_2 concentrations and regulator pressure schedule for an aircraft flying to 50,000 feet with a 5 psi differential pressure cabin.

As mentioned previously, too much O_2 can be toxic to tissues, including the brain. The body has natural mechanism to alter blood flow to limit the development of inflammation or reactive O_2 species in highly metabolic tissues including the central nervous system. These mechanisms generally involve a restriction in blood flow on the order of 10 to 40% depending on the study. Furthermore, this vasoconstriction generally will persist for a period of time after removal of the hyperoxic gas, usually on the order of several minutes or longer. This can create a vulnerable period, if the body is compensating to the hyperoxic gas and the hyperoxic gas is suddenly removed, it places the more metabolically active tissues at risk, especially the Central Nervous

System (CNS). This vulnerable period also appears to include increased inflammation and cellular lung damage when oscillations in hyperoxic concentrations exceed the ability of the homeostasis mechanisms to compensate and keep pace with the continuous changes. Decreases of $\geq$ 20% O_2 concentration also increase absorption atelectasis. If this occurs sequentially and rapidly in less than 5 minutes, the atelectasis is worsened with each swing, due to lack insufficient time to re-inflate with nitrogen Evidence for these conclusions is included in medical literature examined in the Hyperoxia addendum of the PBA report.

Table 8.1. O_2 Change During Each Segment

O_2 change by Segment	Aircraft 1	Aircraft 2
1) Normal Relaxed Breathing	23%	17%
2) 2x Max Inhale/Relaxed Exhale	20%	17%
3) Backup Oxygen System (100% O2) [Expected due to system change to BOS]	[51%]	[58%]
4) Defog Full On (Hi Flow/Hi Temp)	17%	16%
5) 2x Press-to-Test (Mask Off in #2 only) (*Due to Mask Off free flow)	18%	39%*
6) Disconnect G-suit	13%	10%
7) 2x Press-to-Test (w/o G-suit)	17%	16%
8) 2x Max Inhale/Relaxed Exhale w/o G-suit	29%	8%
9) Rapid Deep Breaths (w/o G-suit)	43%	25%
10) Defog Full On (w/o G-suit)	17%	27%
11) Mask Off (w/o G-suit)	38%	25%
12) Engine above Idle (15% w/o G-suit)	18%	20%
13) Connect G-suit [Expected due to system change to 100%]	17%	[49%]
14) Press-to-Test (BOS – 100% Oxygen)	63%	56%
15) 10 timed breaths in #1 / Mask Off in #2 (*Due to Mask Off free flow)	15%	25%*
Average oxygen change per Aircraft [Excluding 3, 13 due to 100% oxygen] (*Excluding 5, 15 due to dissimilar points)	27%	22%

The O_2 swings shown are neither comprehensive, nor representative of airborne performance. The O_2 was always well above 100mmHg, providing sufficient O_2 for minimum requirements at all times. The O_2 variability of the F-35 has been well documented and independently confirmed by the Joint Program Office and Dr. Miller's OBOGS Lab. These data reinforce the importance of understanding and mitigating the physiological impact of high and rapidly varying O_2 concentrations in pilot breathing gas. They also reinforce the importance of end to end systems testing as the data show variations due to systems interactions and aircraft differences.

Compensation: The ability of the human body to compensate for dynamically changing circumstances is remarkable, but finite. Pilot in the Loop Oscillations (PIO) may provide a helpful analogy to explain the pilot/plane interactions in the F-35. In both cases, there are control systems on both sides. The pilot can make adaptive changes either consciously or subconsciously to the system to accommodate system disruptions. These adaptive changes and compensations may be short term (sigh, yawn, etc…) or long term, may take time to work (slightly slower respiration rate), have a response lag, and may have additional side effects of their own over time. These adaptive changes are effective in accommodating small changes, but ineffective in accommodating large changes past some undefined critical point. The decay in effectiveness occurs gradually, and then suddenly. The danger with unrecognized compensation is that breathing margins can be so small that any further breathing challenge can result in rapid decompensation, which will look out of proportion to the proximal cause.

Breathing Distraction: In the F-35, according to interviews, the breathing system forces pilots to think about their breathing. This is a cognitive distraction that divides attention away from mission tasks.

- "...it is routine for me to notice now, put it like this: I NEVER thought about my breathing, EVER, in the Strike Eagle. Never. I never, it was not a conscious though...it was never brought forward into my conscious thinking about breathing, it was just something I was doing and I never considered it. Now it is something that I am conscious of, routinely, in flight; I'm conscious of how I'm breathing, conscious of making sure I'm controlling my breath, taking a deep breath, to expand my lungs every 10/15 minutes or so, I make sure that I do that."

8.3 Physiological Conclusions

Observed breathing dynamic changes and O_2 swings of up to 40% are consistent with interview reports that 50% of pilots have experience mild physiological symptoms at some point in their F-35 flying, and with some pilots experiencing them on a regular basis. The synergistic combination of breathing sequence disruptions (constantly changing pressure, flow, and synchrony) and inconsistent O_2 concentrations may lead to pervasive respiratory dynamics changes, but this is as yet undocumented in flight. Continuous breathing disharmony and pressure/flow asynchrony are consistent with pulmonary Micro-trauma of the alveoli, airways, and chest wall remodeling. The effects of these many disparate physiological responses, in aggregate, can predispose to pathological hypoxia. These factors are all present on the F-35 in this study at levels capable of causing short-term dysfunction or even longer-term harm from chronic inflammation. The physiological changes in response to fluctuations in inspired O_2 concentrations on the order of 40% are not well understood, but highly concerning for contributing to individual PEs or long-term cumulative damage. The destructive synergy of these factors are consistent with the documented permanent damage to lung physiology responsible for the medical retirement of at least one F-35 pilot (based on pilot interview and medical record review), consistent with pilot complaints over the last 8 years, and consistent with interview accounts of symptoms experienced by pilots.

The human is a pressure differential generator, and controls breathing with pressures; however, the breathing system does not appear responsive to a pilot's pressure signals with appropriate flows. The pilot is being forced to adapt physiologically to an unpredictable and oscillatory flow. The result is compensation in the form of lower MV, lower TV, increased functional reserve capacity, and likelihood of atelectasis, increased dead space, micro-trauma, hyperinflation, and an increased predisposition to hypoxia.

Summary of Potential Pulmonary Insults

Pilots flying the F-35 are subjected to various alterations in the breathing dynamics that can cause directly or contribute to distinct respiratory pathophysiology.

Hyperoxia
  a. Absorption atelectasis resulting in decreased lung volumes and altered lung circulation
  b. Cerebrovascular constriction in specific brain regions placing these regions at risk for regional hypoxia

2) Acceleration atelectasis
  a. Decreased tidal volumes, diminished cardiac volume with higher G_z, and chest wall increased work of breathing

3) Rapid Oscillating Hyperoxic concentrations
    a. Accelerated cerebrovascular constriction in specific brain regions resulting in regional hypoxia
4) Breathing System Asynchrony
    a. Asynchronous timing – mechanical triggering of breath lags or leads the pilots breathing cycles. Lagging a breath diminishes tidal volumes delivered to the pilot. Leading a breath (oversupply) induces restricted volumes physiologically to prevent hyperinflation.
    b. Asynchronous volumes or flow – The inspiration flow or volume does not match the pilot's inspiratory effort. Too much volume causes a physiological reaction to limit the volume to prevent hyperinflation or to little reduces TVs
    c. Asynchrony leads to increased work of breathing, excessive fatigue of respiratory muscles, and non-specific respiratory discomfort. Excessive flow or pressure will result in alveolar micro-trauma
5) Inspiratory overpressure
    a. Results in an increase in dead space volume over time
    b. Chest wall muscular remodeling
6) Expiratory overpressure
    a. Results in dynamic hyperinflation, air trapping (increased dead space), and decreased inspired TV
    b. Decreased venous return to the heart causing deceased cardiac output and reduced circulatory pressure and volume (decreased blood pressure)
7) Inspiratory and expiratory overpressure combined
    a. Results in increased dead space volume more rapidly than just inspiratory or expiratory overpressure
        i. Expiratory dynamic hyperinflation results in worsened air trapping (increased dead space) by additional decreased inspiratory TV.
        ii. Higher likelihood of larger areas of micro-trauma and barotrauma
    b. Chest wall muscular remodeling
    c. Combined effect further worsens the individual decreases in venous return to the heart. Substantial reduction in cardiac output and reduces circulatory pressure and volume (decreased blood pressure)

The general hypothesis, as yet untested in the flight environment, is that F-35 breathing dynamics insults, singularly or in combination, could result in cerebral (brain) hypoxia and cognitive disorders, and/or create conditions of increased work of breathing, excessive fatigue of respiratory muscles, and non-specific respiratory discomfort. Furthermore, excessive flow or pressure may lead to alveolar micro-trauma and/or induce alveolar and airway barotrauma. An ongoing program of pulmonary function testing would lead to a better understanding of these results.

9.0 Definition of Terms

Chest Wall Remodel	Inspiratory over pressure usually does not produce hyperinflation unless the peak pressure is excessively high. Because you can breathe out if the expiratory pressure is not excessive, then hyperinflation by itself will not hyperinflate. If tidal volumes are limited to compensate, this is another matter and can lead to hypoxia
Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.

Appendix

Appendix 7.1. Pilot Subjective Report

Appendix 7.1. Pilot Subjective Report

This appendix is a companion to Section 5 to include all recorded pilot comments related to the scope of this exploration. Please see Section 5 for the full explanation and interpretation of the pilot report clusters.

Collection Summary: Five F-35 pilot interviews were conducted by a team of three NESC PBA researchers: a flight surgeon, an F-35 SME, and a human factors SME. Each interviewee was provided a NASA Privacy Act Notice which indicated the protected status of the interview and all materials associated with the interview. All interviewees provided explicit consent to video/audio recording, interview transcription, and inclusion in this report. All data are reported in aggregate to maintain privacy. Each interview began with the pilot account of events related to the flight that induced a reported or unreported PE with specific information about the in-flight event, post-flight procedures, and recovery. This was followed by a period of question and answers for clarification and expansion. Finally, pilots were asked to provide perceptions of overall concepts across all airframes such as breathing experience, previous symptoms, common symptomology, and current processes. Brackets within quotations indicate areas where additional content was provided for context or to omit and substitute sensitive details. Grayed out pilot comments were included in the main body of Appendix 7.

Pre-production testing and program development through to current day mission flights. The early pilot reports:

- "It was trying to kill me"
- "The system was working as designed, but didn't actually protect me"
- "Maybe we had some fundamental misunderstandings of what the design of the system needed to be and we didn't have as much physiological understanding of the human/machine system as we needed."

A pilot noted that, at the time his concerns about the breathing system were raised, there were other on-going investigations specifically related to potential breathing gas contamination concerns. He stated that his concerns were met with program leadership opposition in the form of explicit and implicit rejection and suppression:

- "There was tremendous amount of concern amongst the enterprise that the program was vulnerable, at the time, and so there was a lot of pressure to continue testing, continue pressing forward. The team as a whole, and especially the program office folks who were in charge of the life-support system at the time, were fairly motivated to assign [my symptoms] to something that was not attributed to the jet. That was my perception that was what they were trying to do, find a way to have it not be the jet so they could press."
- "they were able to, again, sort of talk themselves into using those words and saying 'well, maybe it was hypercapnia, maybe it was hyperventilation, but in no case is it something we need to change the design.'"

One pilot reported this summary statement regarding the F-35:

- "It's the new normal. Breathing in this jet is different than sitting here talking to you and breathing. It shouldn't be, in my opinion, but it is. Talking against positive pressure is different than talking against no positive pressure. The schedule of the cockpit pressurization sometimes changes the pressure in the mask, I don't know if it should be doing that or not, sometimes it does do that. The pressure breathing for G is slightly, not slightly, it's different than what I had been previously accustomed to. And so, it is routine for me to notice now, put it like this: I NEVER thought about my breathing, EVER, in the Strike Eagle. Never. I never, it was not a conscious thought, I didn't ever, it was never brought forward into my conscious thinking about breathing it was just something I was doing and I never considered it. Now it is something that I am conscious of, routinely, in flight; I'm conscious of how I'm breathing, conscious of making sure I'm controlling my breath, taking a deep breath, to expand my lungs every 10/15 minutes or so, I make sure that I do that. That could be a factor of this thing happening to me or it could be a factor of just breathing in this jet is different. I think if you were to ask other pilots that they would, my opinion is, of course they have their own opinions, is that the breathing in this jet is different than breathing in the Viper, the F-15 C or E, the A-10, or any other platforms, F-22, that they've come from, even the hornet. We have guys here that have flown all of them. It's just the different apparatus, a different feeling. And so now every sortie I am somewhat conscious of how I'm breathing, and how I'm interacting physiologically with the jet."

Another pilot reported this summary statement regarding his experience in the F-35.

- "The overall experience was one of extreme, you know, it's difficult to convey to other pilots and other people how absolutely disconcerting it is to be cognitively bamboozled like that. Because you know there's something wrong with you, you can't convey it, and you don't know why, and you don't even know the why to the why. Don't even know where to begin. 'Hey, what's wrong with me?' 'I don't know,' well, that only makes it worse, right? Which, okay, potentially psychologically, is just concerning on all levels, even though intellectually you kind of know 'hey, I'll be okay. I'll just go to sleep and this will all…' But for somebody whose entire life you are relying on your brain to be able think, and to fly, and to not be able to connect those words causes of level of concern. The jet attacked me. That's the essence of the way I felt. Even though somebody else might go, 'Oh, you're just a little bit off, go sleep it off, shake it off, shake it off.' Right? This was an entirely different level going through that experience and if it were to have happened while I was still flying, that's the thing that's the most concerning. Right? Because now it calls into question your ability to handle an emergency. That's the interesting dichotomy, I think I could have flown and landed the aircraft if everything was fine, but now it's kind of like the insidious where… you know… you always hear about the people going to sleep in the car in the garage, right, it's kind of the apathetic, just comfortably go crash, right? That's the concern. I would just not be able to make a decision, not be able to think and connect in airborne. If that had happened, there's nothing I could do about it. There's no control over it. As a pilot, you like to be able to control and take what actions you can. Nothing I can do! Nothing I can do to prevent it, fix it, and potentially maybe it's causing long-term harm to my health. So, that's the thing to convey. Maybe it's difficult to convey how that felt. Well, that's it.

To be clear, all pilots identified the F-35 as an asset to the warfighter. Here are a few summary quotes for positivity and perspective:

- "The F-16 had some significant growing pains as it was introduced as far as there were medical factors, it was routinely killing pilots with GLOC and spatial disorientation, but that was several decades ago. With time, effort, investigation, a merging of aerospace and aeromedical efforts, these were overcome and went on to become one of the most successful fighters in history and I'm confident the F 35 will do the same."
- "The jet is still providing an environment that, although not optimal, I don't perceive as actually dangerous. These UPEs certainly merit further investigation, but they haven't killed anybody. I'm gambling my life on it, so I think that's one of the more significant endorsements I can provide.
- "No pilot experienced significant enough symptoms that they have to stop fighting and address that over the tactical problem."
- "Overall, pilots trust the jet."

Pilot Symptom and Perception Clusters

These interviews revealed several pilot symptom and perception clusters. Here, clusters are conceptual groupings that emerged after the identification of highly similar statements and the subsequent interpretation of shared characteristics. Adverse symptomatology was reported across wide spectrum of flight profiles and pilot demographics (e.g., flight hours, age, and expertise). These symptomatology does not appear to be specific to individual differences or task performance. Pilots reported adverse symptomatology across the spectrum of individual differences and characteristics. This range included nascent pilots with low-hour and no previous aircraft experience to elite pilots with instructor qualifications, multiple airframes qualifications, and many hours of previous experience including extensive combat experience. Pilots reported adverse symptomatology across the spectrum of flight regimes ranging from straight and level, administrative, non-demanding phases of flight, to flight that is physically and cognitively intense. Quotes for this cluster have been excluded as detailing individual-specific characteristics of demographic and flight profile would compromise the privacy of our pilots.

The remainder of this section will consist of a cluster title, a summary or description of this cluster, and relevant quotes to demonstrate sufficient support for the grouping.

Cluster 1: The F-35 breathing environment and physiological experience is dissimilar to a) other aircraft flown and b) normal physiologic breathing. The F-35 breathing system noticeably discourages normal breathing function via high-pressure, pressure surges, and hyperoxia.

Quotes include:

- "The respiratory environment is not, still, is not optimized for normal human physiology"
- "That was the first time the jet had attacked me"
- "F-35 is known to produce erratic oxygen output both in concentration and in pressure. Some latency in the pressure delivery, or a lag in the system, as far as the pressure delivery. It's perceptible."
- "What I do know is that breathing in the F-35 is different. Breathing in [Strike Eagle] off of an MSOGS was a different experience than it is breathing out of the F-35. The F-35 is different in the fact that it has positive pressure all the time, not just pressure breathing for G but positive pressure in the mask. It's different in the fact that the ECS environmental control system in the F-35 sometimes surges, sometimes pulls back. It's a different physical environment that you're in and the breathing is different. The cockpit pressurization schedule above 25,000 feet is different, it feels different on your body. It's like hard for me to describe quantitatively the difference, but it's different enough that you feel different."
- "I adapted to the airplane and didn't make good note of that adaptation. There is a threshold of initial initiation of the breath that the pilot has to do. It doesn't do anything until you breathe a bit past some certain threshold and then you begin getting flow. There was this, kind of, general kind of breathing technique that I learned, like I said, I guess it was more subconscious than I initially said just then. Where it was kind of: initiate the breath, then breathe while I have flow, and then you kind of have to exhale a little bit more forcibly, and that sort of stops and resets the valves, and then you can exhale and finish the exhale process. It definitely takes more attention, whether it subconscious or conscious, to breathe in the F 35 than it does in any of the other airplanes that I've flown, including ones I did fly, and I'm trying to remember right, I did fly a couple of other airplanes; F-15s with the OBOGS and a flew an F-18 with the OBOGS, and those I don't remember having any need to adapt my breathing like I had to in the F 35."
- "Tighten specifications on the delivery schedule to reduce that frequent rapid oxygen cycling, pressure and the concentration"
- "You kind of have to begin the exhale as an event, and then once that all starts, and the flow begins, then kind of exhale normally. So, I guess another way to describe it, and this is not an accurate mechanical description, but the feeling was kind of that it was like a sticky valve, both directions. You, kind of, have to pull to get the inbound air going and then once the valve is flowing that I could breathe in with big continuous motion. And the same thing, I had to initiate the exhale, so a sticky valve feeling in that sense, and then once the exhale began, I could just go ahead and exhale normally."
- "When you're breathing off the mask in the F-35 you feel like you have to work a little bit harder so you're a more forceful inhalation, sometimes, you have to more forcefully exhale"
- "The backflow valve would get stuck sometimes. In fact, I remember there would be times I would reach up into the mask and punch the backflow valve if it got jammed. And then that would kind of leave you sometimes with a momentary shortness of breath sensation, I would say, maybe 1 in 10 flights you'll see that."
- "There's a cross valve in the mask, that sometimes if that thing gets gummed up it can be difficult to exhale, I've had that happen."

- “Every time after 100% oxygen you always have kind of a standard Valsalva (mimes a Valsalva, plugs nose and blows), you know, you’ll still have the standard post-high oxygen issues. That’s just normal, normal.”
- “You can hold your breath a lot longer in the 35 because it’s got 100% oxygen. I could go like 50 seconds, a minute, without air hunger.”
- “The positive pressure isn’t really, in my thinking, isn’t so positive. It can be annoying.”
- “Sometimes the F-35 just provides a whole bunch of pressure into the mask for unknown reasons, I don’t know why but it does, it makes exhalation difficult”
- “Increased exhalation pressure. It’s very much perceptible to the pilot as a positive pressure ventilation system”
- “I mostly tend to notice it as expiratory pressure.”
- “Flying the jet you notice, ‘oh, I could actually forcibly exhale more and that would actually be closer to how I would normally breathe.”
- “The amount of oxygen/air I had consumed from the jet was about half of what would had been predicted for someone with my body weight. I had consumed about half the oxygen just due to decreased respiratory rate.”
- “I noticed I tend to have a significantly decreased respiratory rate in this jet.”
- “I think somebody asked me if I was hyperventilating or something, which was ridiculous, I was not anxious, there was no increased respiratory rate.”
- “The ECS does surge. It pulls. So, there’s a single outlet for air that’s between your legs on the center pedestal, if you will. Sometimes that is really providing a lot of flow, as well as the sound of the ECS around you is providing a significant amount of air into the cockpit, and in other times it is not. And it gets warm. Sometimes it pulls the amount of air it’s blowing through the vent and into the cockpit, sometimes that decreases for a couple of minutes. I don’t know what the jet is doing during that time, there’s no change I can tell, it doesn’t really have anything to do with the throttle position, sometimes it does. For instance, on takeoff MIL-power, even into afterburner, the cockpit will surge and then settle. It used to be more significant on the older software suites, where it would, sometimes on takeoff, it would almost completely die in the cockpit and even now, every now and then, even at altitude, it’ll just decrease the volume of air being provided into the cockpit for whatever reason and that’s different. The Eagle did that too, but it was more throttle control. That is something that is unique. It’s not internal to the OBOGS that I can tell. It’s just outside the ECS”
- “Sometimes even in a single exhalation there could be a change in the pressure. So there’s like a kick back and it can actually bite off a radio call.”
- “You’re exhaling against a constant pressure but then it’ll kick back whatever pressure you’re using to exhale and speak, and that pressure is equalized ceasing your exhalation and ceasing your vocalization for the radio transmission.”
- “you’ll be talking and then as you’re talking your expiring and you’re anticipating certain expiratory pressure as you’re talking but within the same exhalation while you’re talking, sometimes it will kick back and it will literally just like (mimes inability to exhale) like stop your expiration and it’ll just, like, cut off your exhalation and talking concurrently, or as a secondary effect, and then you have this oddly clipped radio call.”
- “And then sometimes [the expiratory pressure] will change in the same expiration, like you’ll be expiring, against a certain expiratory pressure and then it’ll kick back at you sometimes or sometimes it’ll go away and it can be somewhat variable, even within the same respiratory cycle. 35 things.”
- “Occasionally, especially on startup, you’ll get a sudden decrease in pressure, so it’s actually like a sudden choking from the jet, - there will be a sudden decrease in flow, pressure that might last like 10 seconds or something like that but then it resolves. But it will get your attention.”
- “not too long after startup after the OBOGS has come online, sometimes it will just dramatically decrease its production and you’re left sucking rubber, so to speak, against the mask, but then it generally clears up in a few seconds. It’s not unique, it’s just an F-35-ism.”

Cluster 2: There is a distinct breathing system disparity across F-35 aircraft with no clear explanation or solution.

Quotes include:

- "There is noticeable change between jets, and some are easy breathers versus more difficult breathers."
- "I do think that the jet breathes differently, each tail number did at least have some subtle variations"
- "Little bit of difficulty getting a deep breath or difficulty breathing off of the OBOGS system. I felt like it was more work than usual but I had seen that before in other flights. Over the course of flying F-35, some days it seems a little bit harder to breathe off the oxygen than others."
- "Difficulty breathing off the oxygen system which led to, kind of, a mild shortness of breath symptom that would come and go, based on how cooperative the breathing system was at the time."
- "It was just a hard-breathing day. And the thing that just stuck in my mind that it was just way harder than normal to breathe without any definitive smoking gun as to what was causing it. I [informed the program office and the head of the maintenance] said 'hey, I just want to give you a heads up, this just breathes strange and it was very hard and it just really caught my attention, but there's nothing… I can't say anything one way or the other for you guys to go fix… So I just wanted to kind of let you know, and just talk it over him you' and they're 'oh, alright, well, just let us know if you think of anything else.' So that was the end of that." The next day I flew an entirely different jet. Same mission, profile, same rough temperature, same place, pretty much everything the same except different jet. Another F-35A. Another Air Force variant. And flew and the breathing was just night and day. So, I went from probably the worst breathing jet that I've ever flown in my life in terms of, it just struck me, that 'hey this is really, really, really, difficult' to nice, easy, breathing, and the contrast between the two of them was just what really caused me to highlight it. So, I thought, 'alright, this is… this is something there. This is real.'"

Cluster 3: Symptoms are frequent and variable among pilots and tend to mimic pilot-specific hypoxia symptoms. However, there are additional individual symptoms that are F-35 specific and learned exclusively from flying the F-35 that suggest additional pathophysiology.

Prominent quotes:

- "Pilots experience symptoms in the jet, they notice, but they're not at the threshold that they consider necessary to declare or that they're willing to flag themselves, highlight themselves, over."
- "There's been a lot of questioning with these events as far as whether or not it is psychogenic but out in the aircraft, I felt no anxiety whatsoever"

Quotes include:

- Hypoxia
  - "I thought immediately that I was hypoxic and that's a big deal."
  - "I noticed hypoxia-like symptoms, but, within about 5 to 10 seconds of noticing those, I received an OBOGS fail caution. I was about 50 miles [away], I turned my emergency oxygen on, I felt better, I landed."
  - "Several minutes into the situation, I realized I was experiencing lightheadedness, which, is kind of my primary symptom"
  - "I noticed that my chest was rising and falling then I realized my heart rate was increased and right about that same time I got a warm sensation in my ears, right around the ear cups. Right about then is when I started to get the general graying, in my experience with hypoxia which is limited to the ROBD and the oxygen chamber, symptoms of hypoxia in my mind"
  - "it's hard to tell if the onset was due to the actual exiting the aircraft or if everything had built up to that point and just went over the edge. You have a higher oxygen concentration in the jet and then when you come out of that, that protective measure is gone and it just felt to me like 10 minutes or so after getting out of the jet, everything just crashed. All. Everything. Onset of cognitive disability and fatigue occurred pretty much at the same time. When it happened, it happened within the span of a minute or two."
  - "about 10 minutes into the flight. I started noticing some numbness in my hands and feet. Kind of some blurred vision as well and I basically just didn't feel right. I felt a little bit off. But I had no

OBOGS cautions, nothing that would indicate that the jet was have any types of pressurization issues, cabin pressure was on schedule as it should be at that altitude. So, everything was fine, in terms of what jet was indicating to me, it's just I didn't feel right. Initially attributed it to potentially some, maybe fatigue, just kind of accumulating from the operational tempo or maybe from working out that morning."

- "After about 10 seconds or so, I felt my hypoxia symptoms from the altitude chamber get to the point where they were now part of my consciousness. So, in hindsight, I would've probably said that they had been gradually coming on, but it became part of my consciousness at that point."
- "When I assessed myself and said 'I've got my hypoxia [symptoms], I think I said 'Preliminary symptoms of hypoxia' is what I said, because again, at that point, me and everybody else were trying everything we could to not cancel the F 35 program so I didn't want to declare the radio that it was trying to kill me, so I said "preliminary symptoms of hypoxia" over the hot mic just to the control room.

- Lightheadedness
  - "Headache, some occasional in-flight or postflight headache."
  - "Lightheadedness and the blurred vision"
  - "Just, like, lightheadedness, not even dizziness or vertigo but just a… it's difficult to characterize lightheadedness beyond feeling lightheaded… slightly spaced out, depending on what you want to call it."
  - "A pronounced lightheadedness in the aircraft which actually resolved in the aircraft on the way back, and post landing confusion with nausea. The confusion probably resolved within, this is an estimate, 30 minutes to an hour later, the nausea probably persisted about an hour and then everything resolved."
- Nausea
  - "It's like a mild upset stomach kind of feeling"
  - "I was experiencing nausea, call it low-grade. It's actually something I get in the jet fairly routinely. I think it's an OBOGS thing."
- Numbness
  - "At one point I noticed [the numbness in my extremities] all the way up to the top of my calf towards my knee on both of my legs. I had only been in the flight for 10 minutes when that onset began. And that's not a normal symptom.
- Vision
  - "My vision grayed even more, my heart rate was high, and I was, I guess, oxygen-hungry would be the word to describe the way I was breathing."
  - "It started on the periphery and it was a graying. Think of it like a color fading, that's really what it was, it was like a color fading on the outside that started to move in with this general, kind of, I wouldn't call it tunneling, it is not a G, like when you're under G, a tunneling like that, where it's kind of, like, dark and then all you see is a tunnel, it was a graying or loss of color that kind of moved in and then stayed. The center of my field of view really was all right and then everything on the outside was grayish/loss of color, I wasn't really able to focus really outside of that inside field of view."
- Air Hunger
  - "I didn't feel like there wasn't physical air being brought into my body, I felt like in the ROBD, I'm breathing but I'm not getting that satisfaction of breathing, I'm not being fulfilled, my breathing isn't doing anything. That's why wanted more. I was air hungry."
  - "It wasn't like there was a huge amount of pressure or a lack of supply, it wasn't a supply issue, it was what was in the supply basically. I felt like I wasn't getting enough air; or enough oxygen."
  - "I'm in a pretty regular relaxed resting heart rate when I'm just cruising so I realized that my volume was significantly increased as was the rate of my breathing was increased."
  - "'I'm feeling like there's less air than I want' kind of a thing, but a mental not a physical breathing air hunger."
  -
- Anxiety
  - "No, [there was no elevated sense of anxiety] I was stereotypically confident that I was handling it just fine"

- “Preemptively going on the BOS at higher altitudes. Which probably sounds like a lack of confidence in the system… maybe it is… but I think it is people being cautious.”
- “I think the symptoms can be, let me just give you an example. Let’s just say that if you stand up too quickly you get lightheaded and you have the same exact symptoms as if you’re hypoxic in ROBD chamber. There’s no difference in the symptoms, but there’s a difference in the cause. The physiological response might be the same, what you feel might be the same, but the cause of it may be different. I just think that I know how my body responds even now to cautions, warnings, things that are going on in the jet, and I have a physiological response to that.”
- “I don’t think that the jet was restricting oxygen content in the breathing gas to me. I DO think that the way that the mask feels, the way that the breathing in the jet feels, the way that the environment feels, I think that all of that was a factor into how I responded physiologically.”
- “As I went through from the beginning of the emergency, I consciously was controlling my breathing. There was, some breathing data available to us as far as rate and depth of breathing, and… they didn’t identify that is being grossly unusual.”
- “As a pilot you’re concerned because ‘I don’t feel right’ you’re worried about your medical license, and your ability to fly more, and you’re telling the world that ‘hey, something’s wrong, with me, because of this plane.’”

- Lungs
  - “[It hurt to breathe] at the top of an attempt to breathe in.”
  - “There was no smoking gun, but it’s just generically difficult to breathe and now I’ve flown three days in a row and the upper chest soreness just stood out as ‘I feel like something is wrong there and again I can’t put a finger on it.’”
  - “I couldn’t fully inflate my lungs [For several hours post-flight]. I’d get that pressure and burning sensation in my lungs, trying to expand my lungs”
  - “you can hold your breath a lot longer in the 35 because it’s got 100% oxygen. So, I tried to hold my breath and when I tried to do that, I had like instant air hunger. So normally, I could go like 50 seconds, a minute, without air hunger… about 10 seconds to 15 seconds just extreme air hunger, like you’re a little kid whose breath is… your face is red and you’re ready to burst. I found that I could progressively hold my breath longer and longer. What was noticeable is when you take a breath in to hold your breath, that pain in the chest would become more prominent, almost like a burning sensation, and it was gradually going away as I would do that more and more. And so, after I did that, I think probably five or six times, I actually started feeling much better, much clearheaded and the fatigue lessened.
  - “I couldn’t take an entire, full, deep breath because the pain… I mean, it wasn’t excruciating or anything, but it was just uncomfortable to the point your body is like “no, no, let’s just stop there.” And then, if you’ve ever stretched a muscle and felt that kind of burning sensation that if you hold it there for 10, 15 seconds it just kind of relaxes and let’s go a little bit. You can do that several times and it just gradually opened up.”
- Cognitive issues
  - “During the flight, I probably could’ve run a checklist. In the heat of it, when it was the worst it was in that decent, probably not. I pretty much had my hands full just maintaining aircraft control and getting the jet down. I was fully committed to that. I was not, at that point, going to be able to run a check list. It would take me a little bit of time to get down, get the jet under control, get to a position below 10,000 feet, and then run a checklist.”
  - “It’s worth noting, after landing, I felt, again, pretty out-of-it, fatigued, and even a little bit confused.”
  - “I was trying to log into the [computer] to document the standard post-maintenance debrief. It’s an incredibly basic thing, just logging into a computer that I’ve done over and over again. But I kept logging in over and over again with the wrong password. I had to ask the maintenance individual there, why I couldn’t log in and they were like ‘you’re straight up using the wrong login name and password.’ It was really obvious to them that it was kind of an inappropriate. I was inappropriately confused at that point. Nothing manifested in the air, but I could definitely detect a cognitive slowing and confusion on the ground, after landing.”
  - “When I was looking at it, I couldn’t remember, I could see that it said [label] and [label] but I couldn’t remember if [label] or if [label] was the one that [did what I wanted] and I was contemplating like “which one is it, which one is it, which one is it, I can’t remember” and I

couldn't think, I couldn't remember [laughs] which is odd because I KNOW that it's [label]. But I couldn't, I couldn't put together."

- "Not tunnel vision per se, but focus lock was the only thing I noticed. You'd stare at something. Your attention will remain locked on something but not vision wise.
- "I'm looking at the switch and I can't remember which direction, which is telling that I'm not cognitively with it, I can't remember which direction to turn the switch. I'm looking at it. I don't know which way to turn it. And I couldn't really read the, because I couldn't see well, couldn't really read the labels on it."
- "Again, I wasn't really with it, and I considered [committing a hazardous error], if you will. And just about the time I get my hand [in position to commit the action], I start to feel little bit better. At this point I had dropped my mask and I start to feel little bit better."
- "I'm just slow. It's like you just stare at something for however long, for 20, 30 seconds and you're like 'I'm just staring at it… and I need to… I know what I need to do… but,' [I can't]."
- "No [I could not fly again immediately after]. Well, I wouldn't have wanted to. I don't think I could have. I would never would have tried to."
- "The cognitive deficit was one of being able to concentrate and I specifically remember not being able to find words. Like the words… I knew the concept or whatever, but I couldn't, you know, I would just sit there, looking somebody for like 20 seconds trying to pull the word out. Never in my life have I had the wheel spin where I knew what it was, and it just never engaged to find the word, is the best way I could describe it."
- "No trouble standing or walking or gross motor skills. Just kind of like, maybe, slow and uncoordinated, would be one way to describe it"
- "I had to fill out a questionnaire is the closest thing I can think to it and just look at the questionnaire and you'd stare at the question for a little while, right, trying just to make heads or tails of it. But I think that was more of a… I didn't have trouble manipulating objects or seeing what they were, it was just the conceptual linkage. The judgment was all fine, all the thoughts were there. That's what struck me the time, is the fact that the thoughts were there, but the linkage was not."
- "I had been lightheaded, by the time I noticed I was experiencing some confusion, I was already on the ground so that didn't elicit any anxiety."
- [Could you have followed a procedure so the T?] "If you gave me 20 minutes to do a 2-minute task, sure."
- I just had a mental block [in flight]. It immediately struck me like, "why can I not remember this?"
- "The cognitive benchmark I remember feeling" "I got in the van after getting out of the aircraft and my [commander]… made a joke… I didn't really think anything of it, but… about three hours in the chamber… I thought was pretty funny. The only real recognition was that, along with a couple other things that people have said between getting out of the jet and then getting back kind of hit me at that point in the chamber."

- Fatigue
  - "I was only airborne 15 minutes but I was probably in the jet for an hour total. Get out. And now I'm feeling just like dog crap. Now everything hits me like a train. And I have cognitive disability, extreme fatigue, and I'm just like out of it. To the point where it's kind of scary. I can't form words properly. People that know me are kind of a little bit scared. That this is just not the normal me. And it's just like you've run a marathon, but worse, and you can't think straight and just want to go home and sleep."
  - "I felt that way for hours: three, four hours"
  - "Fatigued over sleepiness. Fatigued like physically drained, not needing sleep."
  - "You're still dragging for a solid two days afterwards."
  - "[After landing] 1) I was relieved to be back. 2) I was, I was just out of it. Like if you go for a really, really, hard run, I mean like a hard run, and you're done with that workout or you're done with exerting yourself significantly and you feel just a little off, little out of it, tired, that's kind of how I felt. Like I had really exerted myself, which I may have, that may have been the adrenaline wearing off, or it could have been a number of different factors, certainly there was some adrenaline involved in that, my body's reaction to what had just happened, and how I felt, so that was definitely part of it, but I just felt mentally kind of… not sharp. For a while."

- “I tend to experience more post-flight fatigue in the F35 than I have in previous jets. That’s actually really common, among F 35 pilots, previously experienced. Definite postflight fatigue.”
- “I could fly a really intense F-16 sortie, land, and then go to the gym. In the F35, I’ll fly even a fairly relaxed F35 sortie and then I’ll land, and I’ll just be like ‘wow, I really don’t have the energy to go to the gym.’ And that is pretty close to universal. Most pilots experience that. This jet fatigues the pilot more than previous airframes have.”
- “My general stress and workload was so much higher during an F-35 test sortie during those years that if there was any physiological effect, it was rolled into it. I mean, I was exhausted, I was always exhausted. I attributed it at the time, and probably would still… was more because of the mental effort that was involved with just doing the job…the concentration and workload that was associated with the actual testing we are doing.”
- “One of the things that I remember specifically was that the caffeine failed to help at all.”
- “I had excessive fatigue during the mission and after the mission for a while”
- “[After the night’s sleep] I’d say 90% recovered in terms of, you know, no longer super, super, slow like you’re in molasses but just you know you’re dragging.”
- “[I] was tired for the next few days. It took a while to recover from that. It’s very disturbing, both from a personal and psychological point to go through.”
- “It’s not like you just ran a marathon and you’re just super tired. It’s more than that. And it’s different. So, it’s not like being super, super, tired, like you woke up in the middle of the night type of thing, it’s more like sheer exhaustion. And so, I went to bed well before my kids and slept like through the whole night and didn’t feel refreshed in the morning. And caffeine didn’t help.”
- “the fatigue was different than any other fatigue that I’ve ever had”
- “the other thing that was disturbing was how long it took to recover. And this wasn’t the first, and definitely wasn’t the last time, where I go several days after a, what I would have before called, “the hard flight”, you know, just some days were harder than others... people who have been flying. You just wake up, even though you thought you got a good night sleep and you slept for a really long time and you’re still almost as tired when you get up as when you went to bed”
- “the thing that kind of sticks out in my mind, is that, the motivation… it’s like somebody just killed all motivation. I’d be happy to sit behind, you know, play a videogame or just sit there and do something and I wouldn’t be like I was falling asleep, but I had no motivation, to do anything. Like, I’d have a task and it would seem kind of, like, insurmountable.”
- “At least 2.5 - 3 days [to recover]. I don’t specifically recall feeling when I was 100% back. Like I said, this wasn’t the only time, this was probably the most extreme where I had an acute event and took several days to recover, but there were other times where I was just fatigued and still the next day or the day after I was still dragging a little bit. So, at least two days, may have been longer, up to a week. There were a couple of times, where I would, like I remember, I even had a workup after this at some point for chronic fatigue, because I was just dragging week after week with no getting better in sight and this was a perfect example of that. After this for several days.”
- Kind of just hitting a fatigue wall. That first week I would notice that I would hit a point, even if I was doing an isolated exercise or something that everything felt tired, not just what I was working, you know, what I was doing at that time. So, that is the only difference I really noted. But then after about a week, that fully subsided.

* Other People
  - “People were just like ‘you’re not your normal self.’”
  - The flight doctor, multiple times, mentioned that I was not myself until coming out of the chamber. He said “you were low-energy, not a lot of eye contact, there is a persistent nystagmus that he that he noticed.”

Cluster 4: Hypoxia recognition training as it currently exists is not a sufficient match with the respiratory environment in the F-35 when compared to the symptom exhibition and mitigation needs experienced during actual flight.

Quotes include:

* “People figure out their F-35 symptoms, essentially by flying it, as odd as that sounds.”
* “The thing about having a problem with your body while you’re flying is that I don’t have a switch, I don’t have anything I can do to, you know, fix it. I don’t have it checklist to go fix, you know, me. So it can be

very disconcerting, that, you know, I don't have any action I can do. I can descend, you know, but in my mind I'm like 'dude, something is not right with me' and I was also thinking 'if this keeps getting worse at the rate that it is getting worse I am not going to be able to stay conscious' was my thought. That if it continued in the direction it was going I was in trouble."

- "This isn't the hypoxia that you were trained to in UPT, you pull your green ring, or you turn the BOS on, it's a green knob in this aircraft, and you'll *instantly* feel better, kind of like you get in the altitude chamber, but this may be a - then kind of let things settle out for a few minutes and then you should feel better over time but it might require minutes to address the situation and feel better."
- "Ironically enough though, the canopy up, rush of fresh air, did not make me feel better. I basically stayed the same. I didn't really feel normal until about two hours later."
- "I also didn't know what to do with my initial symptoms. Honestly I had never, I mean, you train to it but you don't really think about hypoxia as something that you're going to, I mean you train all the time to other emergency procedures, you know, hydraulic failures things like that, but training to what your body is going to feel like and what you need to do in that situation is different."
- [upon canopy open] "there was really no change. It was not like when I'm in the ROBD and I'm not feeling well and I gang load, and I get that [snaps fingers] rush of oxygen or a new supply, you pretty much right away regain your color vision and all that, it wasn't like there was a huge rush of feeling, "oh my gosh, now the canopy's open and I feel great," it wasn't that. It was, I felt pretty much the same, which was much better than I had in the cockpit 15 minutes earlier but, it wasn't, when I popped the canopy and I got the Oxygen mask, it wasn't like "Oh my god, thank God, I feel so much better" it was "okay, I feel the same as I did about five minutes ago."
- "normally you would go on backup oxygen system, when you are experiencing hypoxia symptoms, or physiologic symptoms, I should say, however, the symptoms occurred after several minutes while breathing the backup oxygen system provisioned so I made a pilot decision and elected to discontinue that and go back onto the OBOGS"
- "I think it's important to talk a little bit about perception versus reality here, so in my mind what I was perceiving was an OBOGS fail, the BOS came on, I did not feel well with the BOS on in my mind, started the decent, now I noticed the OBOGS is back on, I'm below 7000 feet, the BOS is off, and I am now feeling better. I'm confused. I think at that point that there was something wrong with the BOS, the backup oxygen system, maybe a bad supply of air in the bottle and so I did not trust the backup oxygen system at that point so I did not turn the BOS on and I did not drop my mask. I just get my mask up thinking that the OBOGS was okay and that the BOS was bad."
- "I start to have the same symptoms again so: air hungry, not feeling well, and now in my mind I start to think that backup oxygen system is bad and so I don't really have any actions that I can do. I'm kind of at the end of my rope, if you will. The only thing I can do is drop my mask."
- "I had a caution in an aircraft that I was not that familiar with, with 100 hours, in an environment that I was not used to knowing what my body would feel like, and I think that that, again just my opinion, I think that that caution caused a physiological response with me, because the caution system in the F 35 is pretty… loud."
- "I didn't think of controlling that inhale and controlling the exhale. I didn't think about trying to control my heart rate or control my body. I never thought that I would have to think about that. I had not really prepared myself, I guess, to be in that situation to control my rate and depth of breathing so it was kind of on its own. I was doing it subconsciously. I was not consciously controlling my breathing."
- "if a pilot experiences symptoms, than obviously they particularly want to descend to try to mitigate that, but that may or may not be possible [due to the active location]."
- "it was about two and a half later, two hours or so later, that I felt normal"
- "While I did feel the same symptoms, my opinion is that I don't think that there's anything wrong with the jet, I think it was the way that I reacted. Now the [second event in same flight], I don't know. I don't know if there was another physiological response or whatever, but the initial one, I don't know, my guess is that I hyperventilated or I was breathing too much or I had, I don't know, some response where I breathed myself into that, I don't know. It's just what I think."
- "No, [vision problems]. I do have, even now, I have a mental picture of looking at the BOS handle and it looks very clear in my mind's eye now."
- "I had trained on legacy equipment so my expectation, when I flipped the switch for it to go BOS was that there would be a big push of 100% oxygen in my face. Now I know that's not how the system is designed,

so it’s not a surprise that I didn’t get that. And the reason that I flipped the switch, even though I actually had the icon that said BOS on, I still flipped the switch because I wasn’t getting any sort of excess pressure and so I was concerned that ‘Crap, I had an erroneous indication and it hadn’t flipped over’ so I was wanting it, but I’m not sure, I think that may have been just negative training from physiological with legacy equipment.”

- “When I started evaluating myself and realized I had exactly the same hypoxia symptoms as I had experienced… in the altitude chamber. There were always the same, and they were consistent in the jet at that point with what I experienced in the altitude chamber. A little bit of an overall queasiness and then it was that clammy kind of feeling and a bit of a hot skin sort of feeling, and then it would get gradually a little bit more tingly, but still that hot skin, clammy feeling, and then I would get lightheaded, was kind of the progression each of the times”
- “I think there was a discussion at some point whether we need to go to the flight doc and I’m like “Well, I don’t have any symptoms other than I’m just extremely tired, right? And I just can’t quite think straight, you know, what’s the Doc gonna do?” So we didn’t go over to the doc because there was really nothing to report.”
- “In the hypoxia training, everything seems to escalate very quickly. So, you go from normal to hypoxic in about a minute or two minutes. This seemed to be a very slow onset, a very slow ramp-up over the course of about 20 to 30 minutes. I think that’s why it delayed recognition on my part. And then again, usually in our hypoxia training it’s also accompanied by some type of warning or caution that the aircraft gives you or a pressurization failure that you can also correlate to your symptoms. I didn’t have any of those.”
- I was basically constantly trying to let myself know, “Hey, you have no warnings or cautions, your cabin altitude is fine, you know, you’re fine, you’re just fatigued. This isn’t a hypoxia thing, everything looks fine, there’s nothing the jet is telling you is off.” That, contributed with the symptoms being relatively mild and then slow onset is why I delayed recognition on my part.”
- “I didn’t know what it was but I just had this feeling that something wasn’t right. And I kept on trying to essentially reason out the symptoms I was having based on the fact that I had no warnings, cautions or cabin pressure malfunctions.”
- “I opened the canopy but it was nothing immediately noticeable. I noticeably felt better when I was in the ambulance and I got put on oxygen.

Cluster 5: Normalization of deviance.

Quotes include:

- “OBOGS sensor had failed, so there actually was a system failure that had generated that ICAW, it wasn’t just a spurious ICAW that we tended to get back then.”
- “Now thinking back and knowing how I respond in the jet now, how I feel in the jet now, that may also be incorrect. That may be something that’s happening all the time now, and I’m just used to it with 500 hours or so now in the F-35.”
- “I have observed there are a lot fewer OBOGS fails. It used to be a fairly common occurrence in the old block 2 software and it was kind of like a ‘well, just hang out, breathe the BOS, reset your OBOGS, and if it resets, fine,’ and you’d actually just continue with the sortie. I don’t think anybody’s gotten any OBOGS fails recently. It’s certainly a less common occurrence in this software variant.”
- “There generally have been episodes while flying block 3, in fact, when I had my episode, it was a brand-new 3F so early block three jet. So, it certainly doesn’t correlate absolutely, but there were more jet OBOGS issue annunciations”
- “It’s important to emphasize these ICAWs, these OBOGS fails in the 2B software that we were flying at the time, these happened all the time like it was considered a nonevent. In fact, depending on what software subset you had of the software subset you could actually just continue the sortie [after the ICAW cleared].”
- “It was just a hard-breathing day. And the thing that just stuck in my mind that it was just way harder than normal to breathe without any definitive smoking gun as to what was causing it. I [informed the program office and the head of the maintenance] and said ‘this just breathes strange and it was very hard, and it just really caught my attention, but there’s nothing… I can’t say anything one way or the other for you guys to go fix… So, I just wanted to kind of let you know, and just talk it over him you” and they’re “oh, alright, well, just let us know if you think of anything else.’ So that was the end of that. I passed it on its FCF checks and signed it off. It required me to actually sign off the jet and say ‘hey, it’s good to go.’ The OBOGS hose was kinked 50%.”

Cluster 6: Pilots expressed several concerns related to the organizational or leadership elements related to the F-35.

Quotes include:

- "Pilots experience symptoms in the jet, they notice, but they're not at the threshold that they consider necessary to declare or that they're willing to flag themselves, highlight themselves, over."
- "I'm firmly of the belief that it is not a psychogenic phenomenon, for a variety of reasons. These are some very skilled, aggressive pilots. They have no inclination to generate symptoms for themselves."
- "There was tremendous amount of concern amongst the enterprise that the program was vulnerable, at the time, and so there was a lot of pressure to continue testing, continue pressing forward. The team as a whole that the program was vulnerable, at the time, and so there was a lot of pressure to continue testing, continue pressing forward. The team as a whole, and especially the program office folks who were in charge of the life-support system at the time, were fairly motivated to assign any, or my symptoms, I guess, my actual reaction, to something that was not attributed to the jet, I guess was their aim. That was my perception, was that that was what they were trying to do: find a way to have it not be the jet so they could press."
- "There is going to be some hard work that we are going to have to do because I think our assumptions are wrong; that your system worked as designed and this is what the outcome was." "This is a fight I don't have the resources to continue to fight, at the time."
- "We talked our way through it and I advocated for an investigation of the design of the system, because, at least it seemed clear to me that, the system even if it had functioned as designed… and that was a rapid conclusion, that they evaluated how everything worked; all the equipment in the chain from OBOGS and BOS through the PIC through my mask to me everything had functioned as it was designed to and so my concern was if they had designed it to do THIS and not protect me from hypoxia in this sort of a scenario, then we had a problem with the design that we should evaluate where those problems were. At the time there was a significant amount of resistance to doing that, again, their assessment was: it worked as designed, the oxygen system wasn't broken, it was a bleed air problem. No need to continue any investigation into the design of the system, as far as it being available in an emergency where there's no bleed air available for pressurization air or for the pilot."
- "I was advocating that we needed to do some research and understand if, maybe, the fact that the system was working as designed, but didn't actually protect me, maybe we had some fundamental misunderstandings of what the design of the system needed to be and we didn't have as much physiological understanding of the human/machine system as we needed."
- "I learned a lot of words that I didn't know before. Besides hypoxia, they discussed that they thought maybe it was hyperventilation. And maybe not hyperventilation in the sense that I was breathing too often and too shallow, but because I was actually actively trying to control my depth and rate of breathing that I had over-controlled and therefore induced hypoxia symptoms by a sort of self-induced hyperventilation. That was one theory. They also, I learned a word called hypercapnia… they were able to, again, sort of talk themselves into using those words and saying "well, maybe it was hypercapnia, maybe it was hyperventilation, but in no case is it something we need to change the design."

Cluster 7: Other Comments – Not included in Chapter

Other comments the pilots included covered areas such as aircraft ergonomics, aircraft heat signature, mask discomfort, and proposed non-contributory elements.

Quotes include:

- "The flight equipment and the ergonomics of the jet. 80% of us are getting severe back pain 30% are getting severe left leg pain."
- "For comfort, a lot of people will drop the mask for maybe, call it, out of an eight-hour sortie, maybe two hours… three hours with the mask down"
- The heat signature on the jet is pretty significant. Some places… that becomes actually a very significant issue, physiologically, "hey, I was super dehydrated… at takeoff"
- The thermal burden of the flight equipment you're wearing is pretty significant, more significant than previous generations of aircraft
- "Ground ops take a lot longer. F-35 ground ops are notoriously longer, so I was in the jet and breathing off of the system for probably a good 40/35 min. [just on the ground]."

- "The equipment the pilot wears to execute the mission, people mentioned that as a potential causation for the symptoms, but I consider that to be noncontributory. There's some weight, but it doesn't actually result in [any restriction]."
- "Thank you, guys, truly, for doing the work, like I said, that we probably should have started in '12. This is going to be useful for very long time."

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Oxygenation - Hyperoxia

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