NASA Engineering and Safety Center Technical Assessment Report

Volume II

Pilot Breathing Assessment

November 19, 2020

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Technical Assessment Report

Appendix 1: PBA Study Design

- This appendix contains the following examples referenced in Technical Section 1.
  1. A flight test report provided as an example of reports submitted by Pilot Breathing Assessment (PBA) pilots following flight.
  2. A metadata report provided as an example of those submitted by the attending life support specialist for a PBA flight.
  3. PBA Flight cards as executed for Profiles A-F, H (in flight), and Profile G (on the ground). These cards were reviewed during Crew Brief Review (pre-flight), followed and annotated by pilot during flight, and reviewed in Crew De-brief Review.

Flight Cards for PBA Scripted Profiles

- Profile A: High Altitude
- Profile B: AeroBatics
- Profile C: Control
- Profile D: Down low
- Profile E: Elimination of Cabin Pressure
- Profile F: Functional Check Flight
- Profile G: Ground only
- Profile H: Health Check – Standardized Flight Test Profile

1. Typical example of flight test report submitted by the PBA pilot following a flight.

Flight Test Report

Report Date: **02/19/2020**

Directorate/Program Title:

NASA Engineering & Safety Center (NESC)

Project/Task Title:

Pilot Breathing Assessment (PBA) Phase 2

Project Manager or POC:

Mark Hodge

Project Partners: If applicable.

Flight Date:

02/19/2020

Flight No.(s) and Time(s):

- PBA 99 (0.8) Navy Gear Pro E

Flight Location(s):

KEDW

Flight(s) 1 of 1 total planned flights

Completed ☒ **Not Completed** ☐ (Explain below)

Flight Assets: List test/support aircraft, if applicable.

F-18 T/N 846

Ground Assets: If applicable.

Flight(s) Objective: What are we trying to accomplish?

Obtain pilot breathing data and associated aircraft state data from NASA F-18A/B in various flight conditions including:

Benign conditions in a common standard flight profile such as those encountered in a functional check flight

Increased pilot breathing effort flight conditions such as those found in aerobatic/combat maneuvering and high altitudes

Specifically this sortie looked at Navy Gear using profile E (unpressurized) in the F-18B with LOX.

Flight(s) Plan: Describe the planned flight(s)/test points.

*** Profile E Navy gear front / USAF NASA gear in rear seat. Times are in Local. Madgetech sensor was flown in the "map case"

PROFILE E (Flown in RAM/DUMP)

- Mask up 12:34:38 (M1). Taxi 12:47
- Canopy Down 12:57:09 (M2).
- Card 1: Max Power Takeoff/Climb. M3 at 13:00:52 taking the runway. Takeoff at 13:01. Max power Climb start at M4 13:05:13 End of climb M5 @ 13:07:30   Note: Airspeed got low and overshot altitude by 600 ft (12,600) as pilot was looking for traffic.
- Card 2: 12K Talking Scripts M6 @ 13:08:07.
- Card 3: Combat Descent 12K-5K. Start of Descent M7 13:09:30. End of Descent M8 13:11:09.
- Card 4: 8000ft Cabin Altitude. A. G-X 3-4 g/400 KCAS M9 @ 13:12:12 4-5g/450 KCAS M10 @ 13:13:12. B. Level 360 5g/450 KCAS M11 @ 13:14:10
- Card 5: 8000ft Cabin Continued. C. Check-6 Assesment M12@ 13:15:27
- Card 6: "Aerobatics" - Squirrel Cage (airspeed and g profile while holding 8K level) #1 M13 start @ 13:17:32 and end M14 @ 13:20:07, #2 M15 start @ 13:22:07 and end M16 @ 13:24:32, #3 M17 @ 13:28:32 and end M18@ 13:28:03.
- Card 7: High G Maneuvering A. 5g Constant Turn at 8K for 1 min (Started at 500 KCAS and 0.85M). M19 @ 13:31:03 B. "Defensive" BFM for 3 minutes level 8K M20@ 13:33:31.
- Card 8 5K Talking Script. M21 @ 13:38:06
- Card 9 RTB Card. Sim Single Engine. M22@ 13:42:44, Overhead Full Stop (flown by back seat) M23 @ 13:46:44, Landing 1348. Pull Clear M24 @ 13:49:20, Canopy Up M25 @ 13:50:51

Shutdown: Mask Down M26 @ 14:00:50

Flight(s) Execution: Describe the flights/test points actually executed.

- Flight Flown in Navy gear in front cockpit and AF/NASA Gear in rear cockpit. There were no equipemnt issues. RAD-97 and Spirometry done preflight and post flight (front cockpit). Rear cocpit pilot only did Spirometry preflight and post-flight. Surveys completed.

Flight Results:

Test ID: 099-8-846-021920-E0-71-XX

VIGILOX: Front seat: ISB 003 ESB 001 CRU-103 S/N 19820, Madgetech on pilot SN Q59998, Cockpit Madgetech Q59978; Rear Seat: ISB 001, ESB 004 CRU-73 EDOX regulator SN 05858,

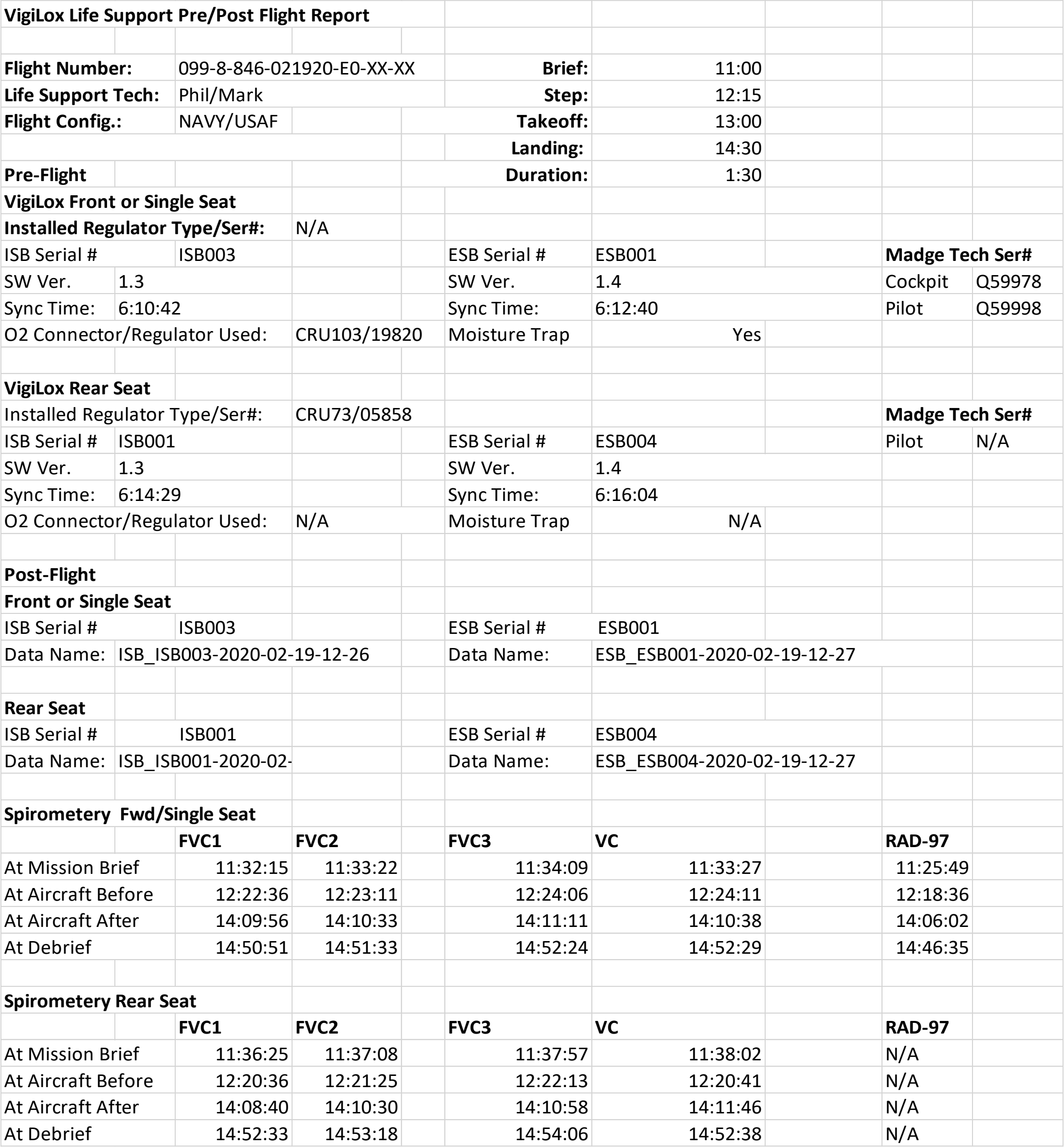
Flight Issues: Discuss any issues experienced during flight test.

Pilots noticed that the Cabin altimeters (front and back) read 1000 ft lower than actual PA.

Next Steps: Upcoming events and milestones.

Additional Comments:

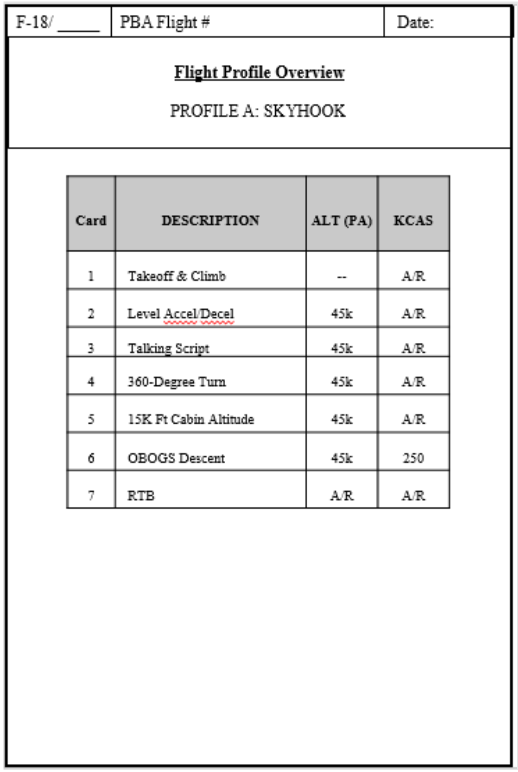
2. A metadata report provided as an example of those submitted by the attending life support specialist for a PBA flight.



VigiLox Life Support Pre/Post Flight Report							
Flight Number:		099-8-846-021920-E0-XX-XX		**Brief:**	11:00		
Life Support Tech:		Phil/Mark		**Step:**	12:15		
Flight Config.:		NAVY/USAF		**Takeoff:**	13:00		
				Landing:	14:30		
Pre-Flight				**Duration:**	1:30		
VigiLox Front or Single Seat							
Installed Regulator Type/Ser#:			N/A				
ISB Serial #		ISB003		ESB Serial #	ESB001	**Madge Tech Ser#**	
SW Ver.	1.3			SW Ver.	1.4	Cockpit	Q59978
Sync Time:	6:10:42			Sync Time:	6:12:40	Pilot	Q59998
O2 Connector/Regulator Used:			CRU103/19820	Moisture Trap	Yes		
VigiLox Rear Seat							
Installed Regulator Type/Ser#:			CRU73/05858			**Madge Tech Ser#**	
ISB Serial #	ISB001			ESB Serial #	ESB004	Pilot	N/A
SW Ver.	1.3			SW Ver.	1.4		
Sync Time:	6:14:29			Sync Time:	6:16:04		
O2 Connector/Regulator Used:			N/A	Moisture Trap	N/A		
Post-Flight							
Front or Single Seat							
ISB Serial #		ISB003		ESB Serial #	ESB001		
Data Name:	ISB_ISB003-2020-02-19-12-26			Data Name:	ESB_ESB001-2020-02-19-12-27		
Rear Seat							
ISB Serial #		ISB001		ESB Serial #	ESB004		
Data Name:	ISB_ISB001-2020-02-			Data Name:	ESB_ESB004-2020-02-19-12-27		
Spirometery Fwd/Single Seat							
		FVC1	**FVC2**	**FVC3**	**VC**	**RAD-97**	
At Mission Brief		11:32:15	11:33:22	11:34:09	11:33:27	11:25:49	
At Aircraft Before		12:22:36	12:23:11	12:24:06	12:24:11	12:18:36	
At Aircraft After		14:09:56	14:10:33	14:11:11	14:10:38	14:06:02	
At Debrief		14:50:51	14:51:33	14:52:24	14:52:29	14:46:35	
Spirometery Rear Seat							
		FVC1	**FVC2**	**FVC3**	**VC**	**RAD-97**	
At Mission Brief		11:36:25	11:37:08	11:37:57	11:38:02	N/A	
At Aircraft Before		12:20:36	12:21:25	12:22:13	12:20:41	N/A	
At Aircraft After		14:08:40	14:10:30	14:10:58	14:11:46	N/A	
At Debrief		14:52:33	14:53:18	14:54:06	14:52:38	N/A	

3. Flight cards as executed for Profiles A-F, H (in flight), and Profile G (on the ground).

Profile A: High Altitude

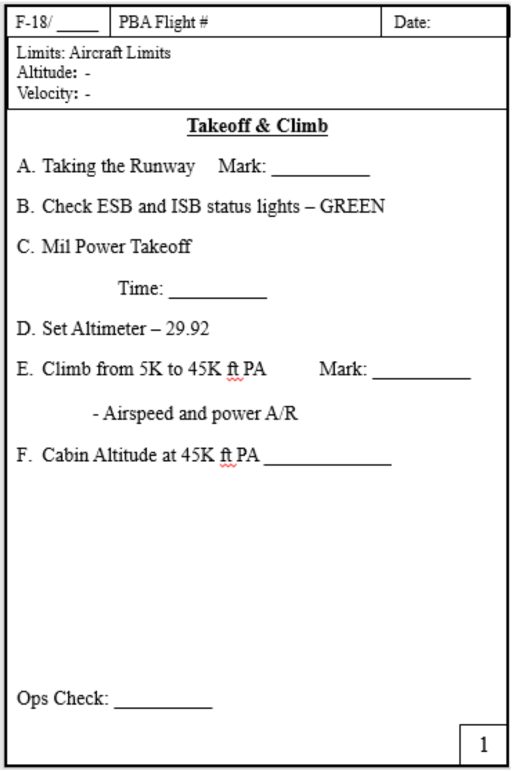


F-18/ _____	PBA Flight #	Date:

Flight Profile Overview

PROFILE A: SKYHOOK

Card	DESCRIPTION	ALT (PA)	KCAS
1	Takeoff & Climb	--	A/R
2	Level Accel/Decel	45k	A/R
3	Talking Script	45k	A/R
4	360-Degree Turn	45k	A/R
5	15K Ft Cabin Altitude	45k	A/R
6	OBOGS Descent	45k	250
7	RTB	A/R	A/R



F-18/ _____	PBA Flight #	Date:

Limits: Aircraft Limits
Altitude: -
Velocity: -

Takeoff & Climb

A. Taking the Runway Mark: __________

B. Check ESB and ISB status lights – GREEN

C. Mil Power Takeoff

Time: __________

D. Set Altimeter – 29.92

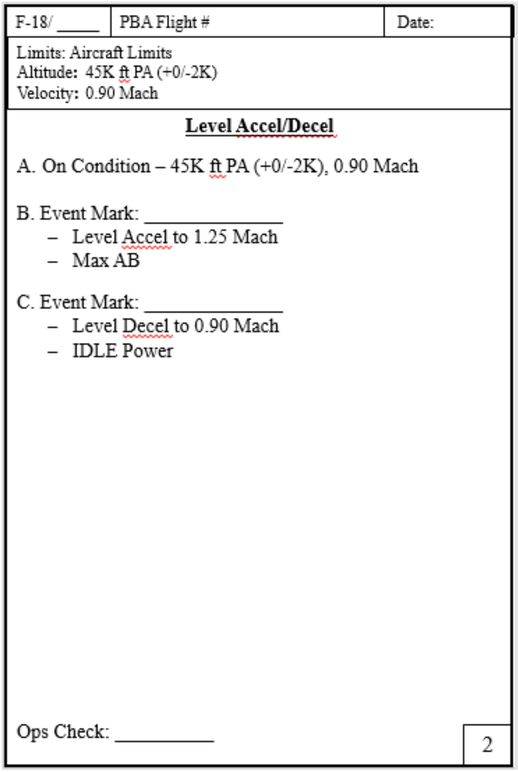
E. Climb from 5K to 45K ft PA Mark: __________

- Airspeed and power A/R

F. Cabin Altitude at 45K ft PA ____________

Ops Check: __________

1



F-18/ _____	PBA Flight #	Date:

Limits: Aircraft Limits
Altitude: 45K ft PA (+0/-2K)
Velocity: 0.90 Mach

Level Accel/Decel

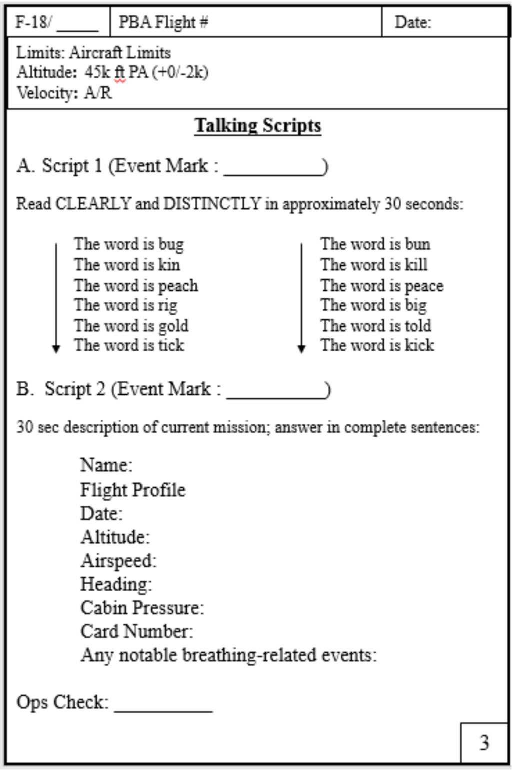
A. On Condition – 45K ft PA (+0/-2K), 0.90 Mach

B. Event Mark: ____________
- Level Accel to 1.25 Mach
- Max AB

C. Event Mark: ____________
- Level Decel to 0.90 Mach
- IDLE Power

Ops Check: __________

2



F-18/ _____	PBA Flight #	Date:

Limits: Aircraft Limits
Altitude: 45k ft PA (+0/-2k)
Velocity: A/R

Talking Scripts

A. Script 1 (Event Mark : __________)

Read CLEARLY and DISTINCTLY in approximately 30 seconds:

The word is bug
The word is kin
The word is peach
The word is rig
The word is gold
The word is tick

The word is bun
The word is kill
The word is peace
The word is big
The word is told
The word is kick

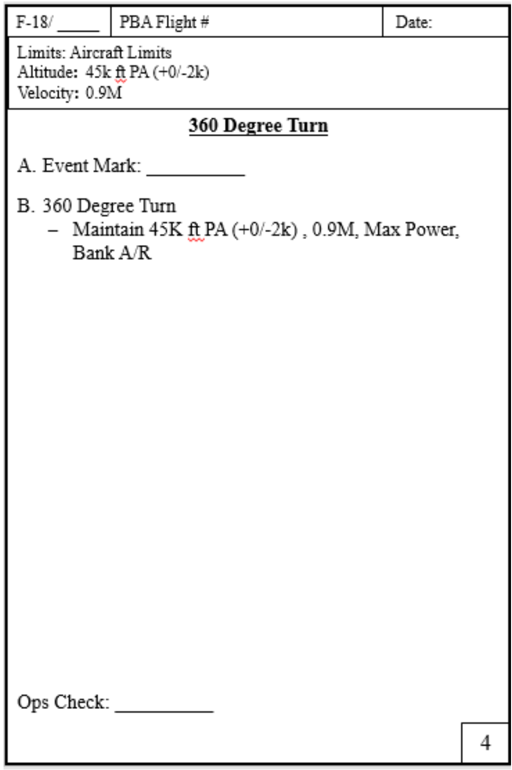
B. Script 2 (Event Mark : __________)

30 sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

3



F-18/ _____ PBA Flight # Date:

Limits: Aircraft Limits
Altitude: 45k ft PA (+0/-2k)
Velocity: 0.9M

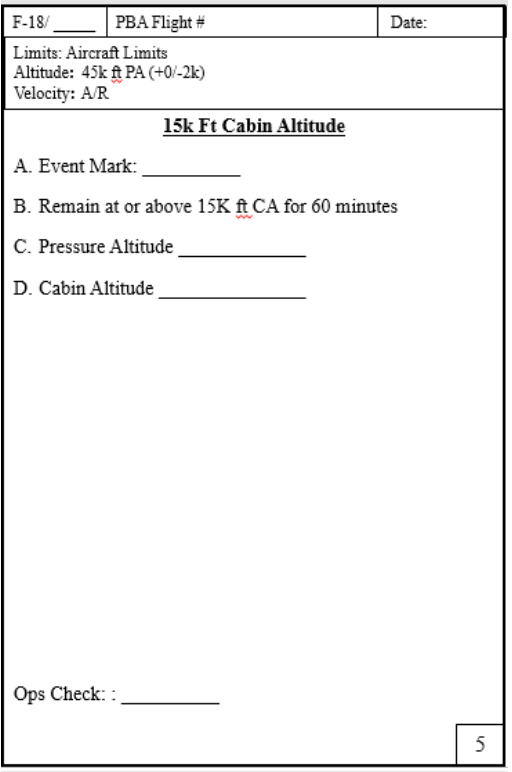
360 Degree Turn

A. Event Mark: __________

B. 360 Degree Turn
  – Maintain 45K ft PA (+0/-2k) , 0.9M, Max Power, Bank A/R

Ops Check: __________

4



F-18/ _____ PBA Flight # Date:

Limits: Aircraft Limits
Altitude: 45k ft PA (+0/-2k)
Velocity: A/R

15k Ft Cabin Altitude

A. Event Mark: __________

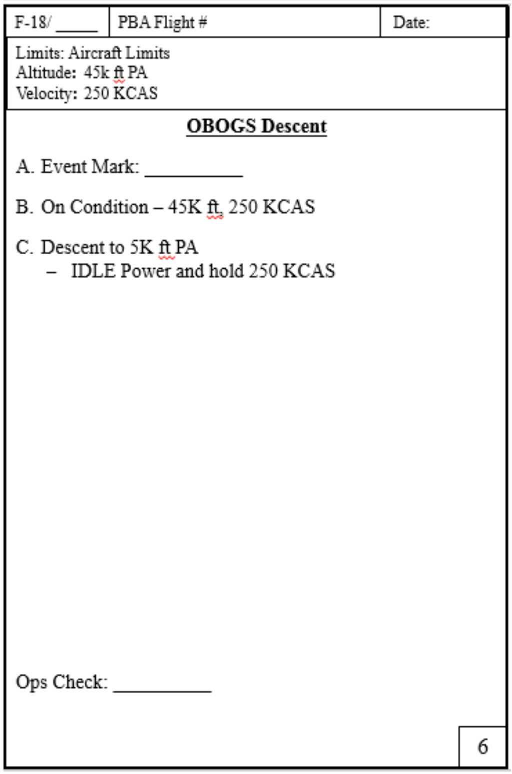
B. Remain at or above 15K ft CA for 60 minutes

C. Pressure Altitude _____________

D. Cabin Altitude _______________

Ops Check: : __________

5



F-18/ _____ PBA Flight # Date:

Limits: Aircraft Limits
Altitude: 45k ft PA
Velocity: 250 KCAS

OBOGS Descent

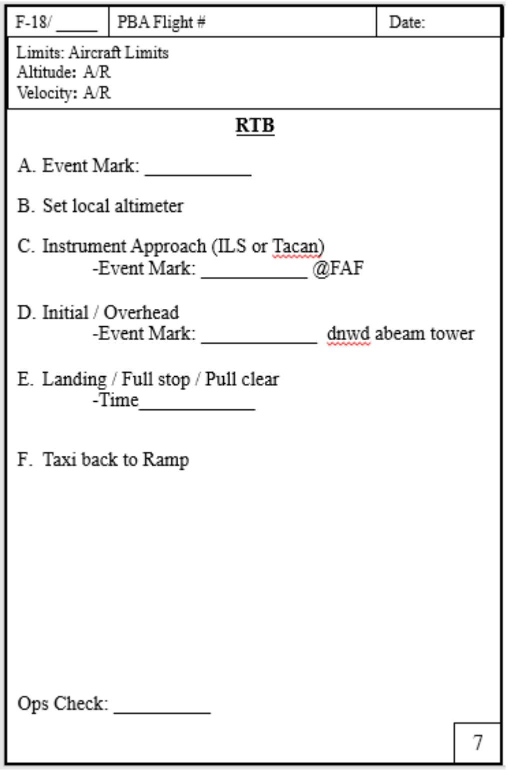
A. Event Mark: __________

B. On Condition – 45K ft, 250 KCAS

C. Descent to 5K ft PA
  – IDLE Power and hold 250 KCAS

Ops Check: __________

6



F-18/ _____ PBA Flight # Date:

Limits: Aircraft Limits
Altitude: A/R
Velocity: A/R

RTB

A. Event Mark: ___________

B. Set local altimeter

C. Instrument Approach (ILS or Tacan)
  -Event Mark: ___________ @FAF

D. Initial / Overhead
  -Event Mark: ____________ dnwd abeam tower

E. Landing / Full stop / Pull clear
  -Time____________

F. Taxi back to Ramp

Ops Check: __________

7

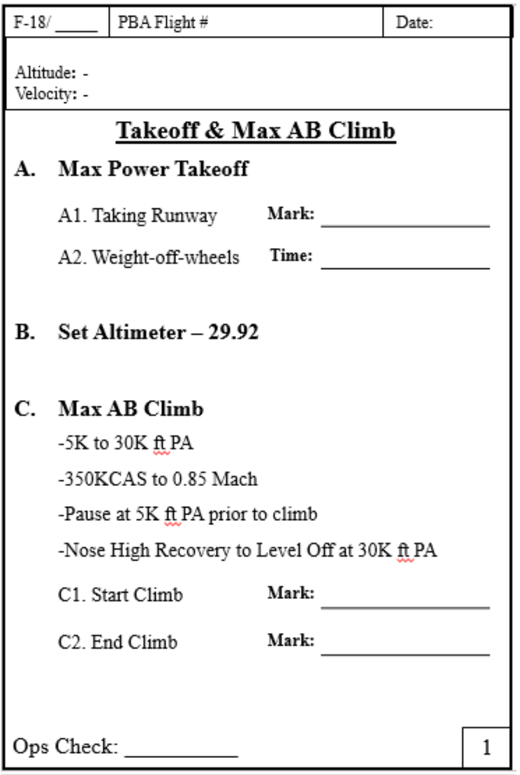
Profile B: AeroBatics

F-18/ ____	PBA Flight #	Date:

Flight Profile Overview

PROFILE B: AEROBATICS

Card	DESCRIPTION	ALT (PA)	KCAS
1	Takeoff & Max AB Climb	SFC – 30K	350 KCAS
2	30K Talking Script	30K	250-300 KCAS
3	Combat Descent	30-5K	350-420 KCAS
4	8000 ft Cabin Altitude	15K	300-450 KCAS
5	8000 ft Cabin Altitude cont.	15K	300-450 KCAS
6	Aerobatics	15-25K	200-450 KCAS
7	High G Maneuvering	5-20K	300KCAS-0.95M
8	5K Talking Script	5K	300-350 KCAS
9	RTB	A/R	A/R



F-18/ ____	PBA Flight #	Date:

Altitude: -
Velocity: -

Takeoff & Max AB Climb

A. Max Power Takeoff

A1. Taking Runway **Mark:** ______________

A2. Weight-off-wheels **Time:** ______________

B. Set Altimeter – 29.92

C. Max AB Climb

-5K to 30K ft PA

-350KCAS to 0.85 Mach

-Pause at 5K ft PA prior to climb

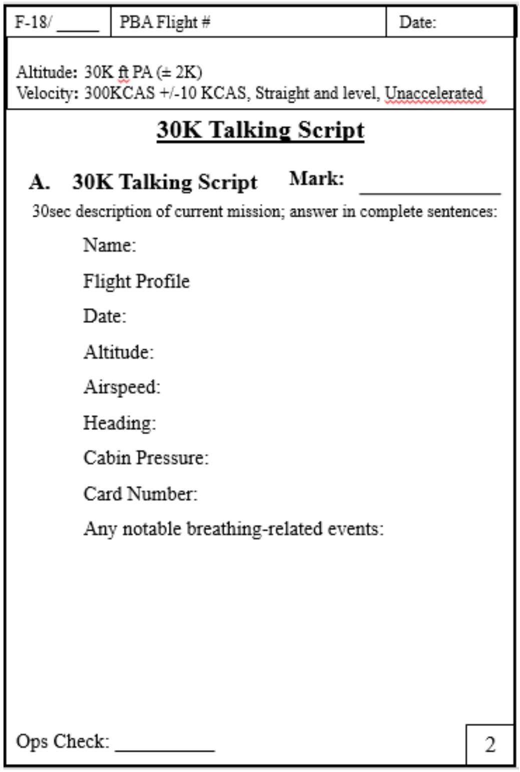
-Nose High Recovery to Level Off at 30K ft PA

C1. Start Climb **Mark:** ______________

C2. End Climb **Mark:** ______________

Ops Check: __________

1



F-18/ ____	PBA Flight #	Date:

Altitude: 30K ft PA (± 2K)
Velocity: 300KCAS +/-10 KCAS, Straight and level, Unaccelerated

30K Talking Script

A. 30K Talking Script **Mark:** ______________

30sec description of current mission; answer in complete sentences:

Name:

Flight Profile

Date:

Altitude:

Airspeed:

Heading:

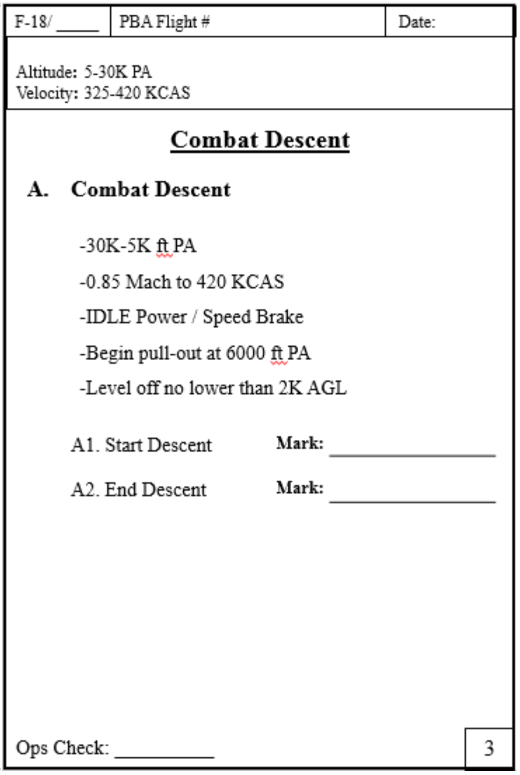
Cabin Pressure:

Card Number:

Any notable breathing-related events:

Ops Check: _________

2



F-18/ ____	PBA Flight #	Date:

Altitude: 5-30K PA
Velocity: 325-420 KCAS

Combat Descent

A. Combat Descent

-30K-5K ft PA

-0.85 Mach to 420 KCAS

-IDLE Power / Speed Brake

-Begin pull-out at 6000 ft PA

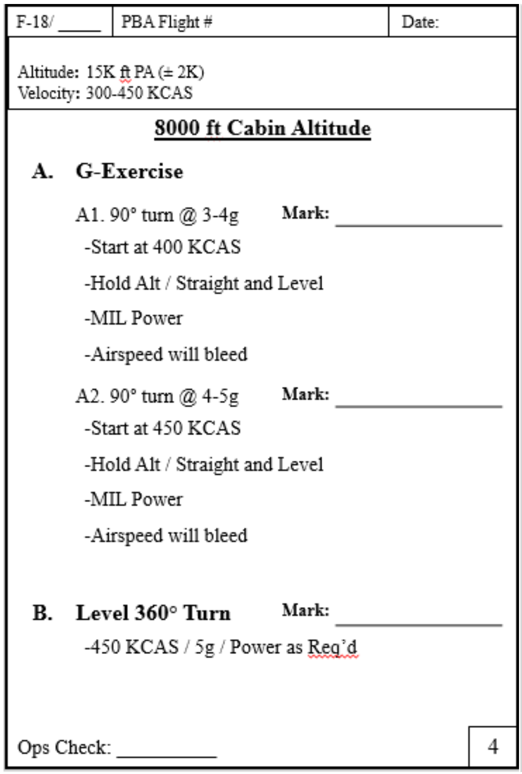
-Level off no lower than 2K AGL

A1. Start Descent **Mark:** ______________

A2. End Descent **Mark:** ______________

Ops Check: _________

3



F-18/ _____ PBA Flight # Date:

Altitude: 15K ft PA (± 2K)
Velocity: 300-450 KCAS

8000 ft Cabin Altitude

A. G-Exercise

A1. 90° turn @ 3-4g **Mark:** ______________

-Start at 400 KCAS

-Hold Alt / Straight and Level

-MIL Power

-Airspeed will bleed

A2. 90° turn @ 4-5g **Mark:** ______________

-Start at 450 KCAS

-Hold Alt / Straight and Level

-MIL Power

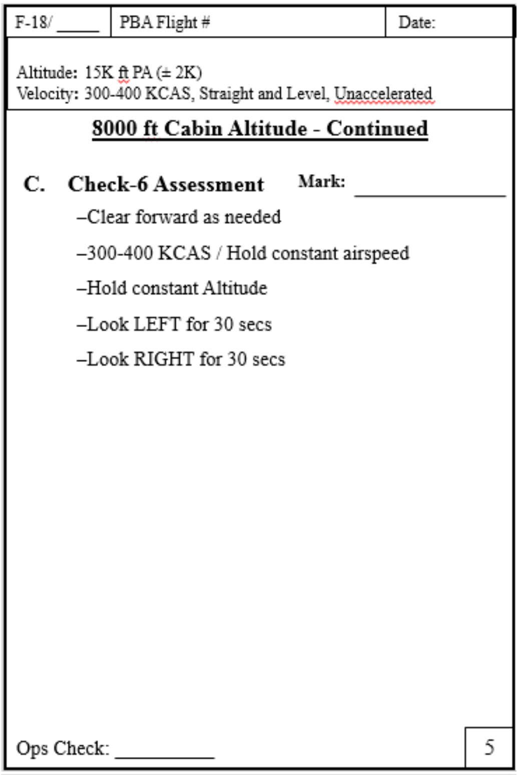
-Airspeed will bleed

B. Level 360° Turn **Mark:** ______________

-450 KCAS / 5g / Power as Req'd

Ops Check: __________

4



F-18/ _____ PBA Flight # Date:

Altitude: 15K ft PA (± 2K)
Velocity: 300-400 KCAS, Straight and Level, Unaccelerated

8000 ft Cabin Altitude - Continued

C. Check-6 Assessment **Mark:** ______________

–Clear forward as needed

–300-400 KCAS / Hold constant airspeed

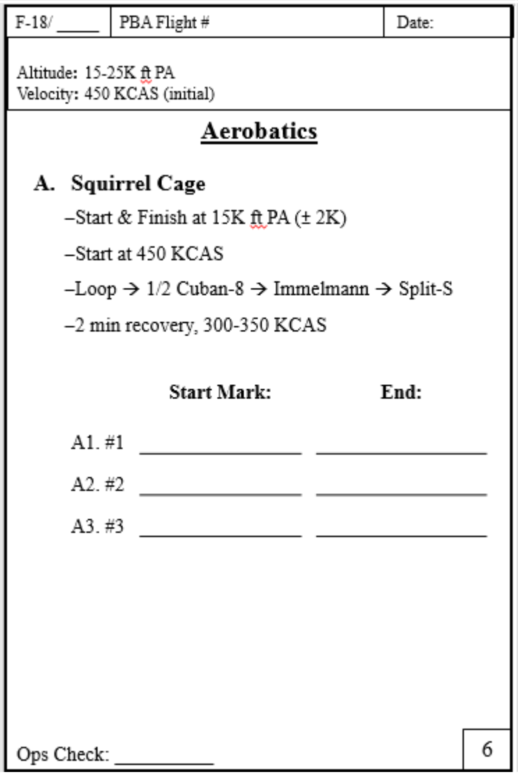
–Hold constant Altitude

–Look LEFT for 30 secs

–Look RIGHT for 30 secs

Ops Check: __________

5



F-18/ _____ PBA Flight # Date:

Altitude: 15-25K ft PA
Velocity: 450 KCAS (initial)

Aerobatics

A. Squirrel Cage

–Start & Finish at 15K ft PA (± 2K)

–Start at 450 KCAS

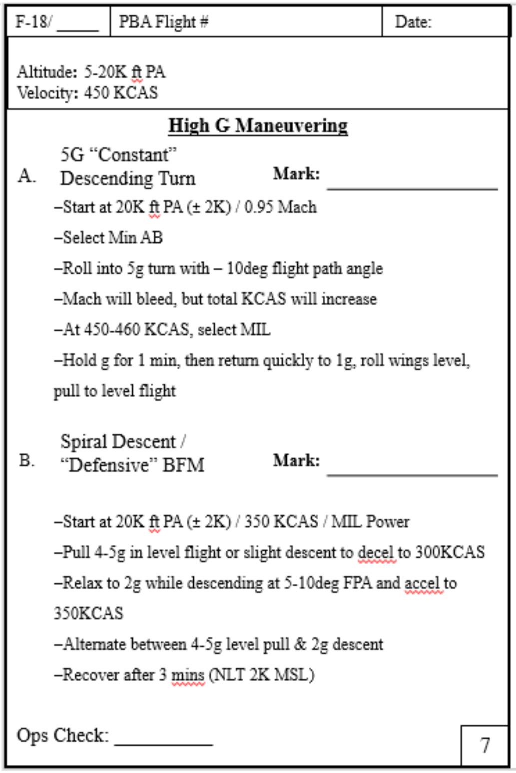
–Loop → 1/2 Cuban-8 → Immelmann → Split-S

–2 min recovery, 300-350 KCAS

	Start Mark:	**End:**
A1. #1	______________	______________
A2. #2	______________	______________
A3. #3	______________	______________

Ops Check: __________

6



F-18/ _____ PBA Flight # Date:

Altitude: 5-20K ft PA
Velocity: 450 KCAS

High G Maneuvering

A. 5G "Constant" Descending Turn **Mark:** ______________

–Start at 20K ft PA (± 2K) / 0.95 Mach

–Select Min AB

–Roll into 5g turn with – 10deg flight path angle

–Mach will bleed, but total KCAS will increase

–At 450-460 KCAS, select MIL

–Hold g for 1 min, then return quickly to 1g, roll wings level, pull to level flight

B. Spiral Descent / "Defensive" BFM **Mark:** ______________

–Start at 20K ft PA (± 2K) / 350 KCAS / MIL Power

–Pull 4-5g in level flight or slight descent to decel to 300KCAS

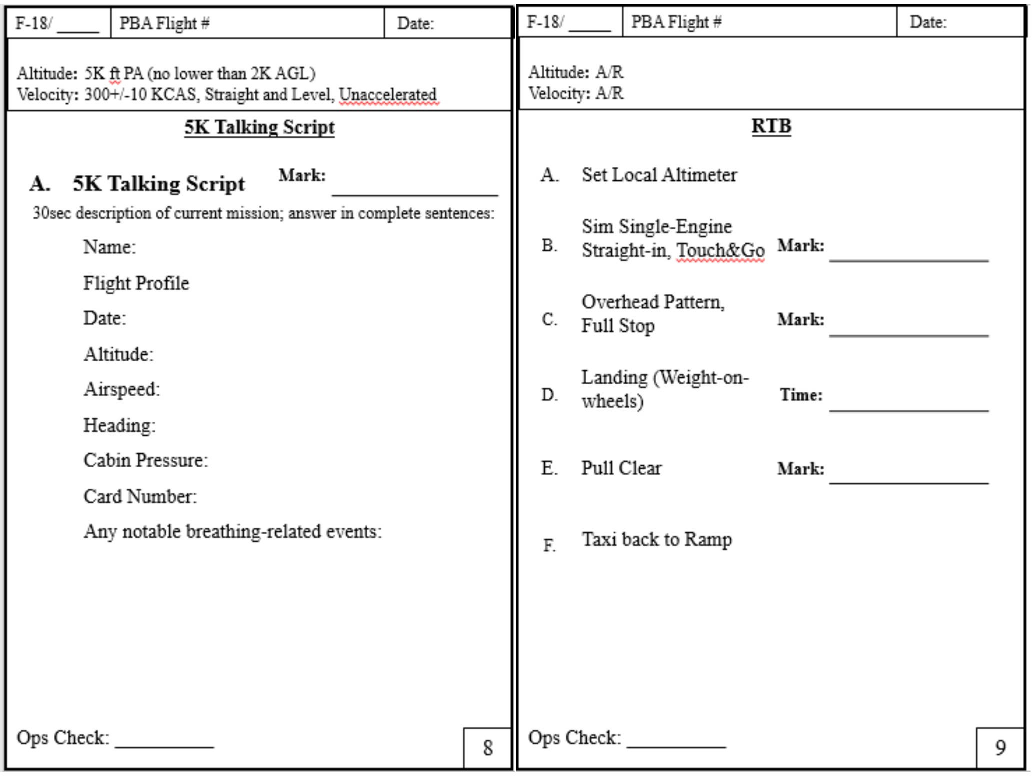
–Relax to 2g while descending at 5-10deg FPA and accel to 350KCAS

–Alternate between 4-5g level pull & 2g descent

–Recover after 3 mins (NLT 2K MSL)

Ops Check: __________

7



F-18/ _____ PBA Flight # Date:

Altitude: 5K ft PA (no lower than 2K AGL)
Velocity: 300+/-10 KCAS, Straight and Level, Unaccelerated

5K Talking Script

A. 5K Talking Script **Mark:** ________________

30sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

8

F-18/ _____ PBA Flight # Date:

Altitude: A/R
Velocity: A/R

RTB

A. Set Local Altimeter

B. Sim Single-Engine Straight-in, Touch&Go **Mark:** ________________

C. Overhead Pattern, Full Stop **Mark:** ________________

D. Landing (Weight-on-wheels) **Time:** ________________

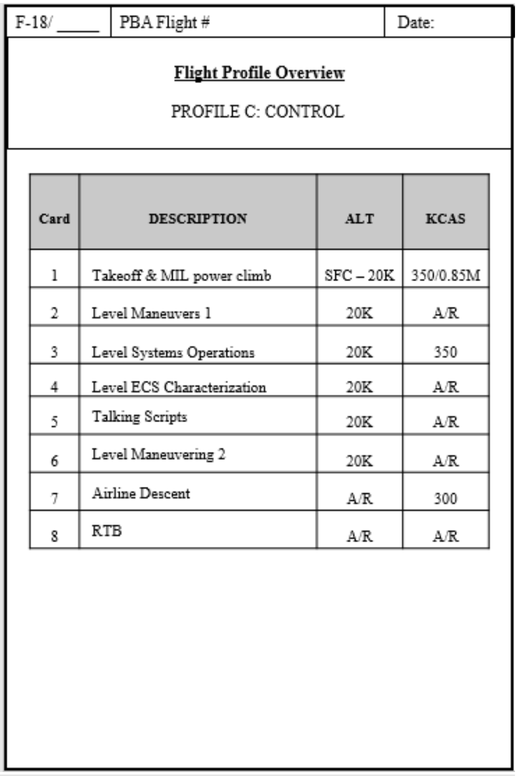
E. Pull Clear **Mark:** ________________

F. Taxi back to Ramp

Ops Check: __________

9

Profile C: Control

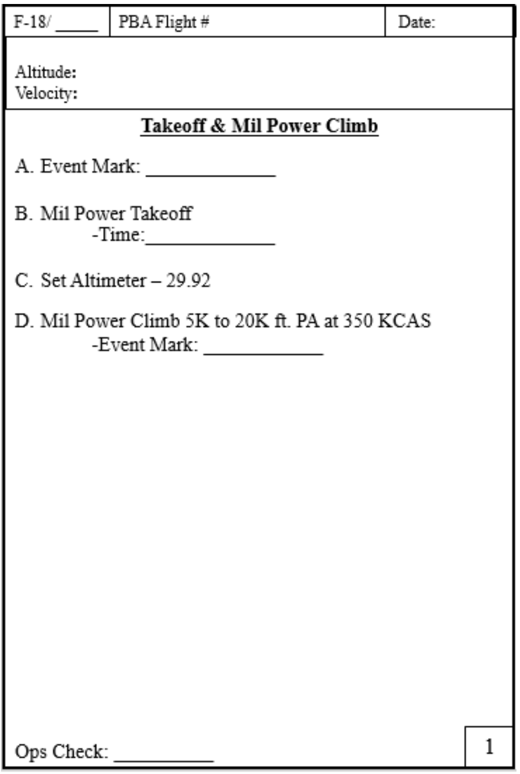


F-18/ _____	PBA Flight #	Date:

Flight Profile Overview

PROFILE C: CONTROL

Card	DESCRIPTION	ALT	KCAS
1	Takeoff & MIL power climb	SFC – 20K	350/0.85M
2	Level Maneuvers 1	20K	A/R
3	Level Systems Operations	20K	350
4	Level ECS Characterization	20K	A/R
5	Talking Scripts	20K	A/R
6	Level Maneuvering 2	20K	A/R
7	Airline Descent	A/R	300
8	RTB	A/R	A/R



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

Takeoff & Mil Power Climb

A. Event Mark: _____________

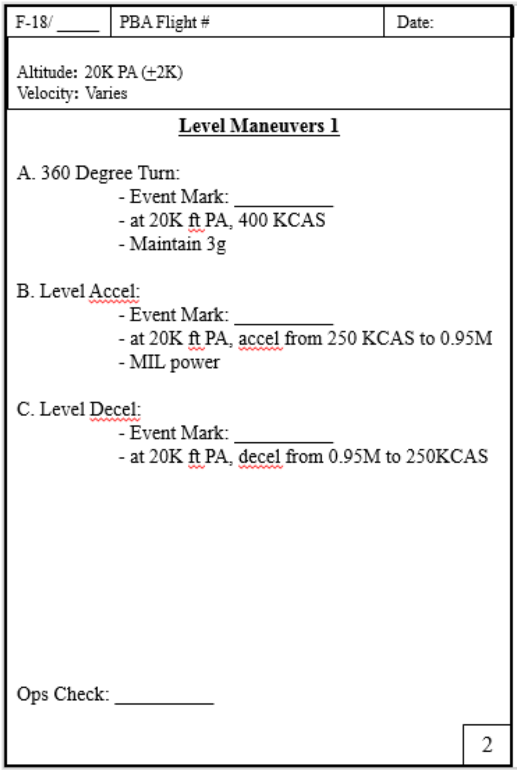
B. Mil Power Takeoff
-Time:_____________

C. Set Altimeter – 29.92

D. Mil Power Climb 5K to 20K ft. PA at 350 KCAS
-Event Mark: ____________

Ops Check: __________

1



F-18/ _____	PBA Flight #	Date:

Altitude: 20K PA (±2K)
Velocity: Varies

Level Maneuvers 1

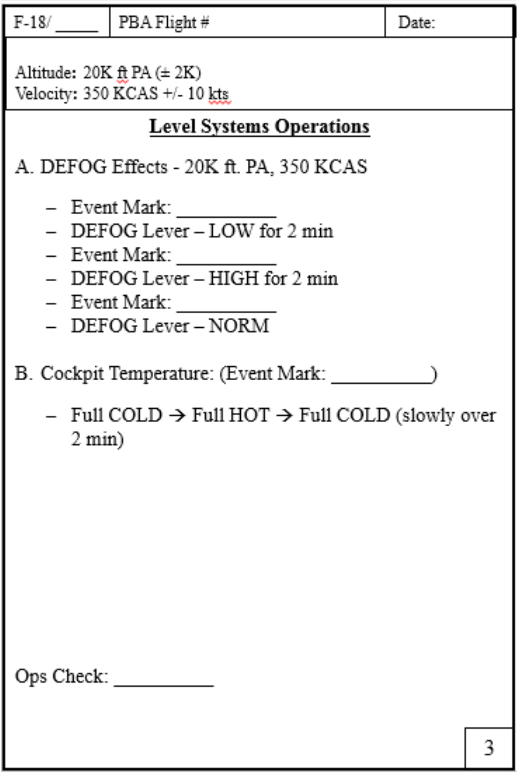
A. 360 Degree Turn:
- Event Mark: __________
- at 20K ft PA, 400 KCAS
- Maintain 3g

B. Level Accel:
- Event Mark: __________
- at 20K ft PA, accel from 250 KCAS to 0.95M
- MIL power

C. Level Decel:
- Event Mark: __________
- at 20K ft PA, decel from 0.95M to 250KCAS

Ops Check: __________

2



F-18/ _____	PBA Flight #	Date:

Altitude: 20K ft PA (± 2K)
Velocity: 350 KCAS +/- 10 kts

Level Systems Operations

A. DEFOG Effects - 20K ft. PA, 350 KCAS

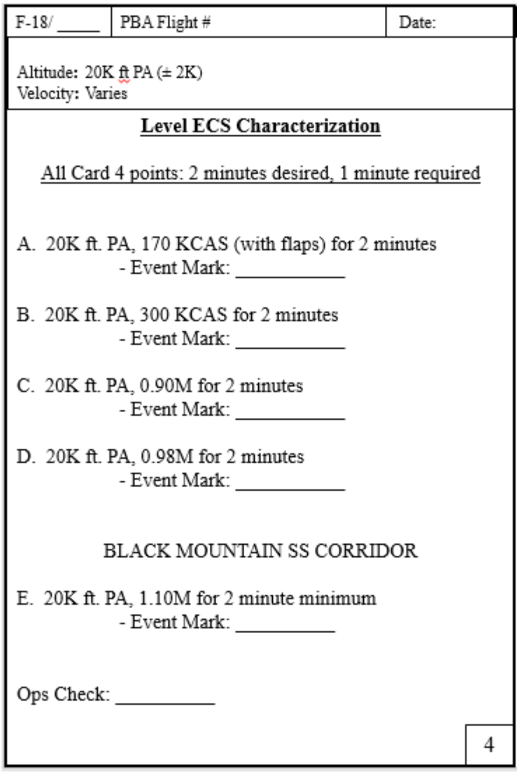
- Event Mark: __________
- DEFOG Lever – LOW for 2 min
- Event Mark: __________
- DEFOG Lever – HIGH for 2 min
- Event Mark: __________
- DEFOG Lever – NORM

B. Cockpit Temperature: (Event Mark: __________)

- Full COLD → Full HOT → Full COLD (slowly over 2 min)

Ops Check: __________

3



F-18/ _____	PBA Flight #	Date:

Altitude: 20K ft PA (± 2K)
Velocity: Varies

Level ECS Characterization

All Card 4 points: 2 minutes desired, 1 minute required

A. 20K ft. PA, 170 KCAS (with flaps) for 2 minutes
- Event Mark: ___________

B. 20K ft. PA, 300 KCAS for 2 minutes
- Event Mark: ___________

C. 20K ft. PA, 0.90M for 2 minutes
- Event Mark: ___________

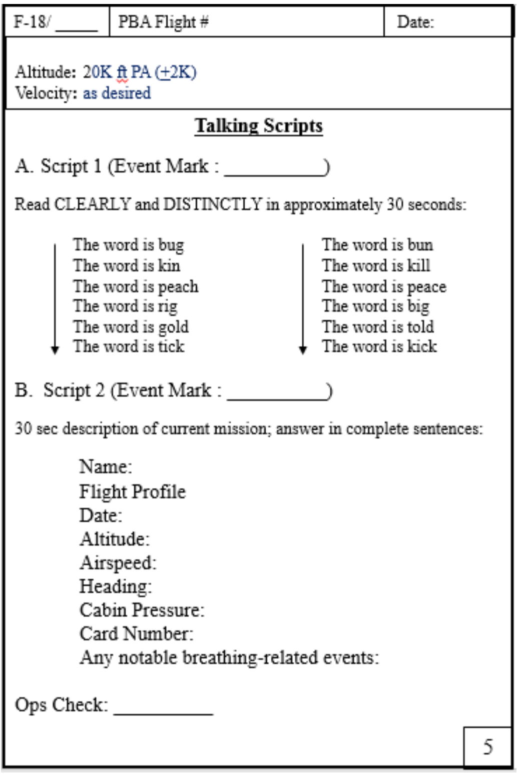
D. 20K ft. PA, 0.98M for 2 minutes
- Event Mark: ___________

BLACK MOUNTAIN SS CORRIDOR

E. 20K ft. PA, 1.10M for 2 minute minimum
- Event Mark: __________

Ops Check: __________

4



F-18/ _____	PBA Flight #	Date:

Altitude: 20K ft PA (±2K)
Velocity: as desired

Talking Scripts

A. Script 1 (Event Mark : __________)

Read CLEARLY and DISTINCTLY in approximately 30 seconds:

The word is bug
The word is kin
The word is peach
The word is rig
The word is gold
The word is tick

The word is bun
The word is kill
The word is peace
The word is big
The word is told
The word is kick

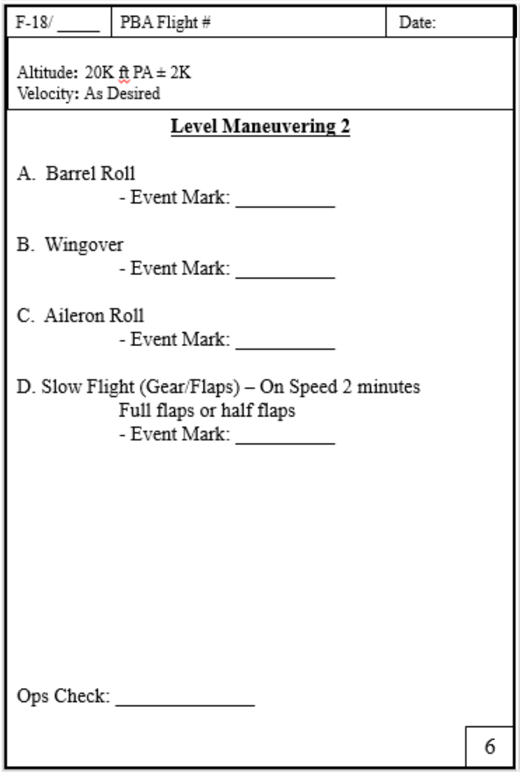
B. Script 2 (Event Mark : __________)

30 sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

5



F-18/ _____	PBA Flight #	Date:

Altitude: 20K ft PA ± 2K
Velocity: As Desired

Level Maneuvering 2

A. Barrel Roll
- Event Mark: __________

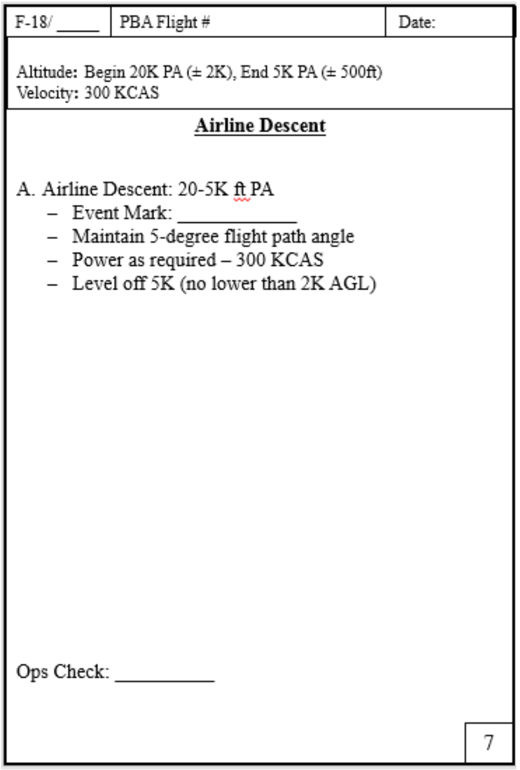
B. Wingover
- Event Mark: __________

C. Aileron Roll
- Event Mark: __________

D. Slow Flight (Gear/Flaps) – On Speed 2 minutes
Full flaps or half flaps
- Event Mark: __________

Ops Check: ______________

6



F-18/ _____	PBA Flight #	Date:

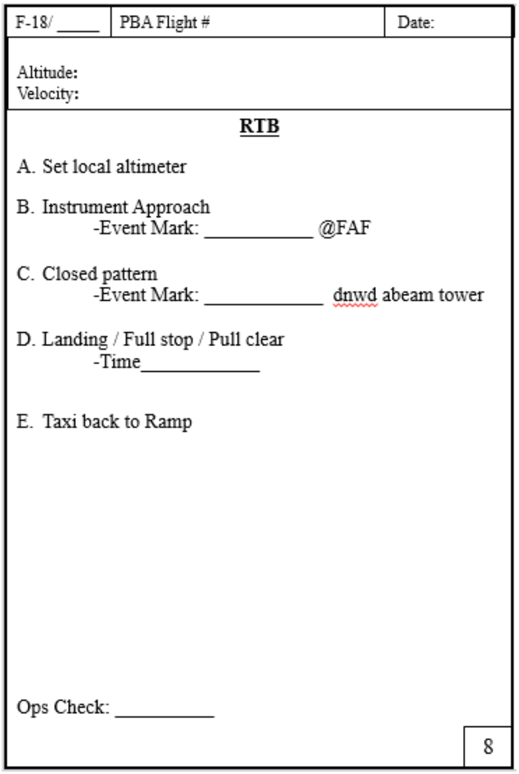
Altitude: Begin 20K PA (± 2K), End 5K PA (± 500ft)
Velocity: 300 KCAS

Airline Descent

A. Airline Descent: 20-5K ft PA
- Event Mark: ____________
- Maintain 5-degree flight path angle
- Power as required – 300 KCAS
- Level off 5K (no lower than 2K AGL)

Ops Check: __________

7



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

RTB

A. Set local altimeter

B. Instrument Approach
-Event Mark: ___________ @FAF

C. Closed pattern
-Event Mark: ____________ dnwd abeam tower

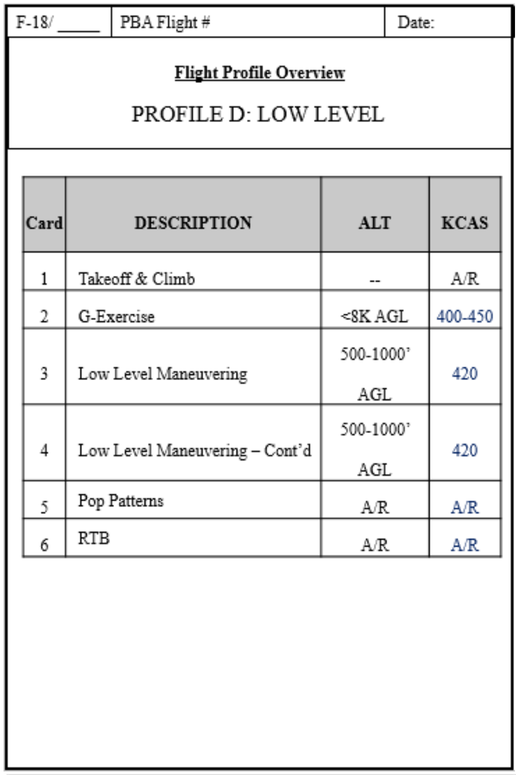
D. Landing / Full stop / Pull clear
-Time____________

E. Taxi back to Ramp

Ops Check: __________

8

Profile D: Down low



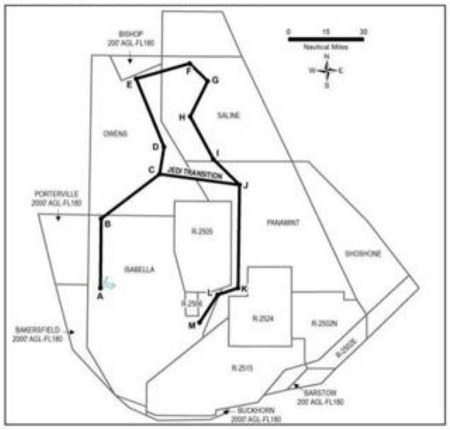
F-18/ ____	PBA Flight #	Date:

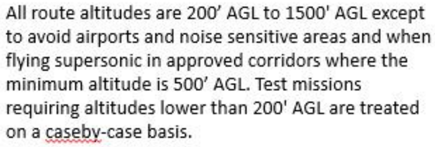
Flight Profile Overview

PROFILE D: LOW LEVEL

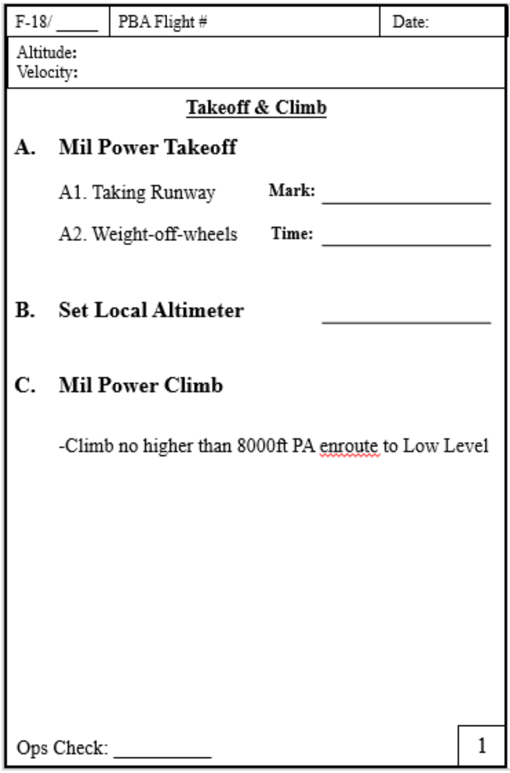
Card	DESCRIPTION	ALT	KCAS
1	Takeoff & Climb	--	A/R
2	G-Exercise	<8K AGL	400-450
3	Low Level Maneuvering	500-1000' AGL	420
4	Low Level Maneuvering – Cont'd	500-1000' AGL	420
5	Pop Patterns	A/R	A/R
6	RTB	A/R	A/R

Figure 10.1. Sidewinder Jedi Transition Low Level.





All route altitudes are 200' AGL to 1500' AGL except to avoid airports and noise sensitive areas and when flying supersonic in approved corridors where the minimum altitude is 500' AGL. Test missions requiring altitudes lower than 200' AGL are treated on a caseby-case basis.



F-18/ ____	PBA Flight #	Date:

Altitude:
Velocity:

Takeoff & Climb

A. Mil Power Takeoff

A1. Taking Runway **Mark:** ______________

A2. Weight-off-wheels **Time:** ______________

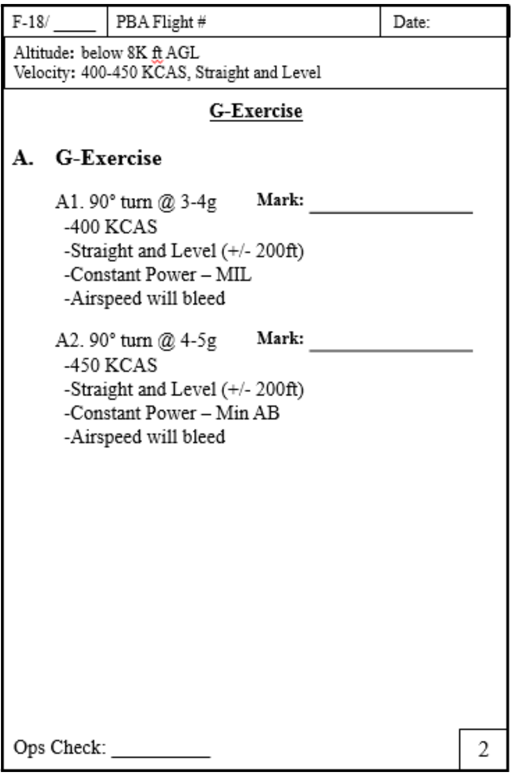
B. Set Local Altimeter ______________

C. Mil Power Climb

-Climb no higher than 8000ft PA enroute to Low Level

Ops Check: ________

1



F-18/ ____	PBA Flight #	Date:

Altitude: below 8K ft AGL
Velocity: 400-450 KCAS, Straight and Level

G-Exercise

A. G-Exercise

A1. 90° turn @ 3-4g **Mark:** ______________
-400 KCAS
-Straight and Level (+/- 200ft)
-Constant Power – MIL
-Airspeed will bleed

A2. 90° turn @ 4-5g **Mark:** ______________
-450 KCAS
-Straight and Level (+/- 200ft)
-Constant Power – Min AB
-Airspeed will bleed

Ops Check: ________

2

F-18/ ____	PBA Flight #	Date:

Altitude: 500-1000 ft AGL
Velocity:

Low Level Maneuvering

Aircraft altitude below 8000 ft PA

A. Fly Low Level Route

- 500-1000ft AGL
- 20-30 minutes / 420 KGS

A1. Start **Mark:** ____________

A2. End **Mark:** ____________

B. Level Accel **Mark:** ____________

- 250 to 550 KCAS/0.95M or V_{mil}
- 1000 ft AGL
- Mil Power

C. Level Decel **Mark:** ____________

- V_{mil} or 550 KCAS/0.95M to 250 KCAS
- 1000ft AGL
- Idle Power

D. Level 360° Turn **Mark:** ____________

- 400 KCAS / 1000ft AGL
- Mil Power / G as-required

Ops Check: _________

3

F-18/ ____	PBA Flight #	Date:

Altitude: 500-5000 ft AGL
Velocity:

Low Level Maneuvering – Cont'd

Aircraft altitude below 8000 ft PA

A. Nose Slice – Roll Angle Test

- Set 29.92
- 5000ft PA / 400KCAS
- Set +15° FPA / Roll 90° bank
- Neutralize Stick/ Hold 1 G / Let nose slice
- -15° FPA / Adjust power to maintain 400 KCAS

A1. Roll Right **Mark:** ____________

A2. Roll Left **Mark:** ____________

B. Wings Level Sideslip

- Keep 29.92
- 400KCAS / 5000ft AGL
- Hold Rudder for 30 seconds
- Hold Altitude (+/- 100 ft)

B1. Left Rudder 1° **Mark:** ____________

B2. Left Rudder 2° **Mark:** ____________

B3. Right Rudder 1° **Mark:** ____________

B4. Right Rudder 2° **Mark:** ____________

Ops Check: _________

4

F-18/ ____	PBA Flight #	Date:

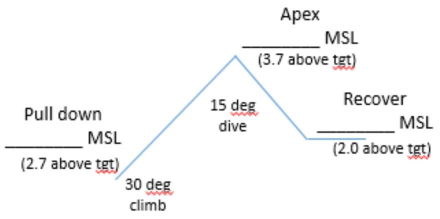
Altitude:
Velocity:

Pop Patterns

A. Set local altimeter

B. 2 x 15-Degree pop patterns

Target Altitude: ________ MSL



B1. Pop Pattern 1: ___________ (10nm from target)

B2. Pop Pattern 2: ___________ (10nm from target)

- Run In @ 500' AGL / 420 KCAS
- Action 30 deg left/right @ 4.8 nm from tgt
- Pull up 30 deg using 4g / Mil power
- Roll in @ 2700' above tgt
- Apex @ 3500' above tgt
- Recover @ 2000' above tgt: 4g in 2 sec / Mil power

Ops Check: _________

5

F-18/ ____	PBA Flight #	Date:

Altitude:
Velocity:

RTB

A. Set Local Altimeter

B. Tower Fly-By @ 450 KCAS **Mark:** ____________

C. Instrument Approach **Mark:** ____________

C. Normal Overhead **Mark:** ____________

D. Landing (Weight-on-wheels) **Time:** ____________

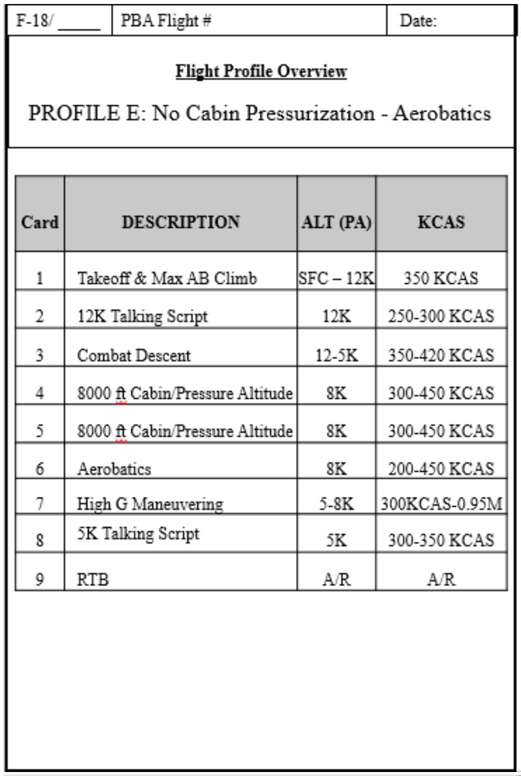
E. Pull Clear **Mark:** ____________

F. Taxi back to Ramp

Ops Check: _________

6

Profile E: Elimination of Cabin Pressure



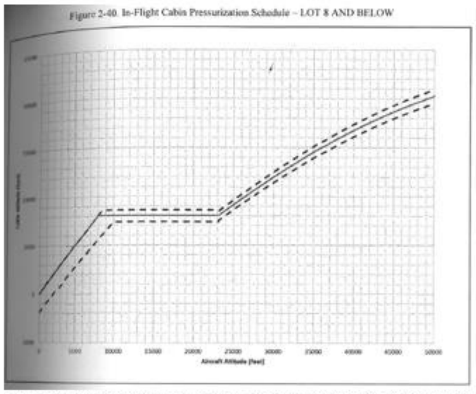
F-18/ ____	PBA Flight #	Date:

Flight Profile Overview

PROFILE E: No Cabin Pressurization - Aerobatics

Card	DESCRIPTION	ALT (PA)	KCAS
1	Takeoff & Max AB Climb	SFC – 12K	350 KCAS
2	12K Talking Script	12K	250-300 KCAS
3	Combat Descent	12-5K	350-420 KCAS
4	8000 ft Cabin/Pressure Altitude	8K	300-450 KCAS
5	8000 ft Cabin/Pressure Altitude	8K	300-450 KCAS
6	Aerobatics	8K	200-450 KCAS
7	High G Maneuvering	5-8K	300KCAS-0.95M
8	5K Talking Script	5K	300-350 KCAS
9	RTB	A/R	A/R

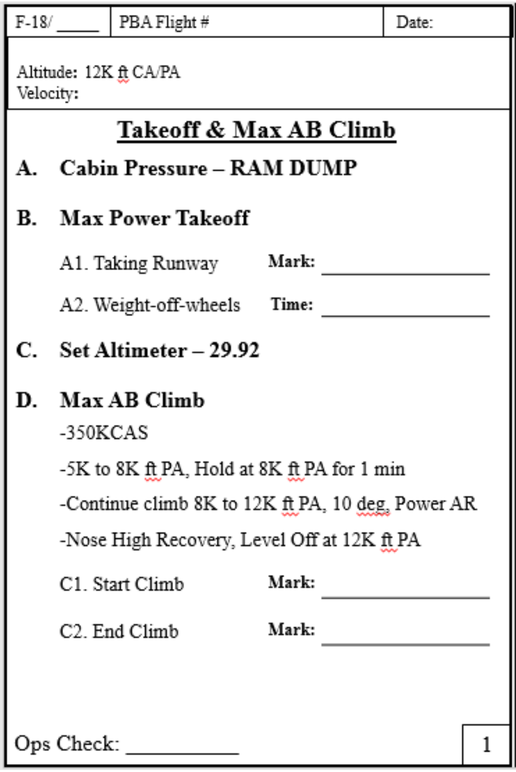
Figure 2-40. In-Flight Cabin Pressurization Schedule – LOT 8 AND BELOW



3.14.7. **High Altitude Operations.** Without functional pressure suits, maintain a cabin altitude below FL250 and adhere to the time limits in Table 3.2. (T-1). For high-altitude airdrop missions, use the oxygen requirements in AFI 11-409, *High Altitude Airdrop Mission Support Procedures*. If the aircraft lands between missions and the time on the ground equals or exceeds the time spent at or above a cabin altitude of FL210, the time of allowable duration can be reset to the maximum (T-1).

Table 3.2. Cabin Altitude Time Limits (DCS Prevention) (N/A for U-2 Operations).

Time (minutes)	Cabin Altitude (ft. MSL)
0	At or Above FL 250
45	24,000 – 24,999
70	23,000 – 23,999
120	22,000 – 22,999
200	21,000 – 21,999



F-18/ ____	PBA Flight #	Date:

Altitude: 12K ft CA/PA
Velocity:

Takeoff & Max AB Climb

A. Cabin Pressure – RAM DUMP

B. Max Power Takeoff

A1. Taking Runway **Mark:** ______________

A2. Weight-off-wheels **Time:** ______________

C. Set Altimeter – 29.92

D. Max AB Climb

-350KCAS

-5K to 8K ft PA, Hold at 8K ft PA for 1 min

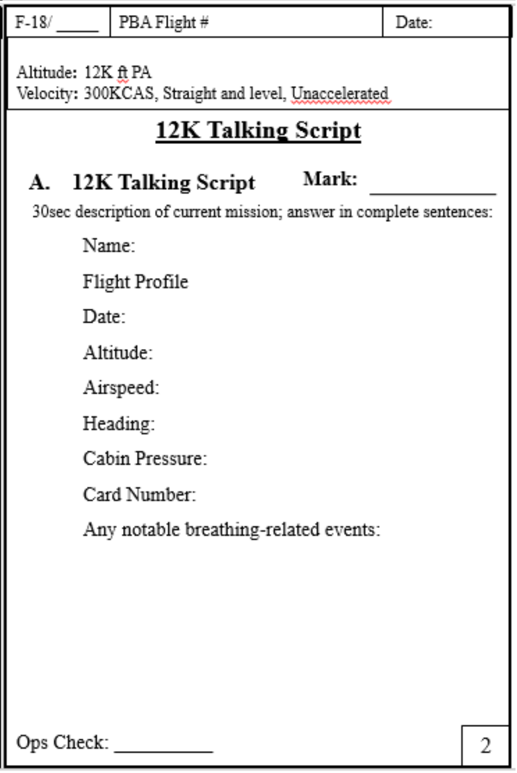
-Continue climb 8K to 12K ft PA, 10 deg, Power AR

-Nose High Recovery, Level Off at 12K ft PA

C1. Start Climb **Mark:** ______________

C2. End Climb **Mark:** ______________

Ops Check: __________ 1



F-18/ ____	PBA Flight #	Date:

Altitude: 12K ft PA
Velocity: 300KCAS, Straight and level, Unaccelerated

12K Talking Script

A. 12K Talking Script **Mark:** __________

30sec description of current mission; answer in complete sentences:

Name:

Flight Profile

Date:

Altitude:

Airspeed:

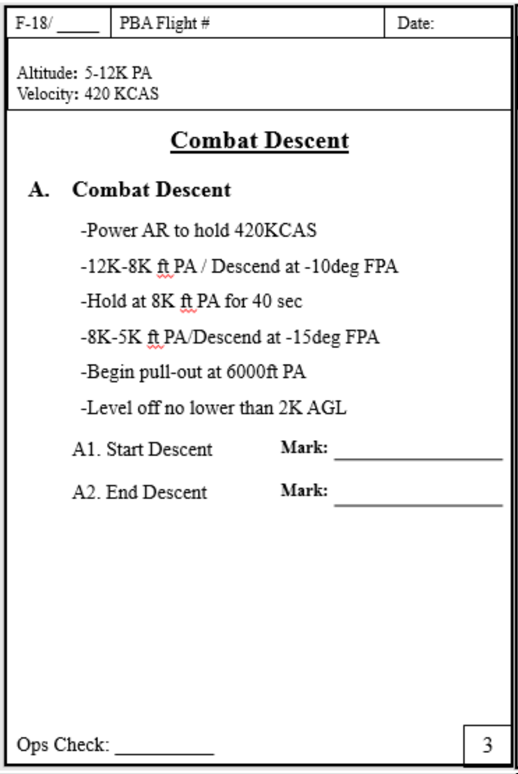
Heading:

Cabin Pressure:

Card Number:

Any notable breathing-related events:

Ops Check: _________ 2



F-18/ ____	PBA Flight #	Date:

Altitude: 5-12K PA
Velocity: 420 KCAS

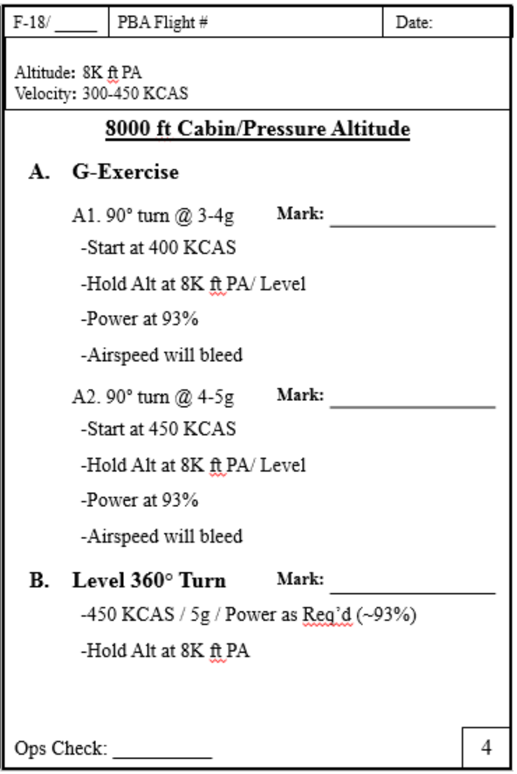
Combat Descent

A. Combat Descent

-Power AR to hold 420KCAS
-12K-8K ft PA / Descend at -10deg FPA
-Hold at 8K ft PA for 40 sec
-8K-5K ft PA/Descend at -15deg FPA
-Begin pull-out at 6000ft PA
-Level off no lower than 2K AGL

A1. Start Descent **Mark:** ________________
A2. End Descent **Mark:** ________________

Ops Check: __________ 3



F-18/ ____	PBA Flight #	Date:

Altitude: 8K ft PA
Velocity: 300-450 KCAS

8000 ft Cabin/Pressure Altitude

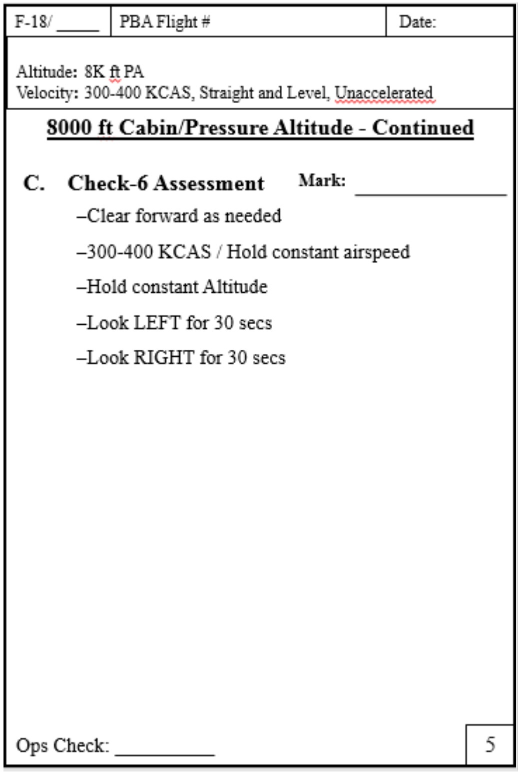
A. G-Exercise

A1. 90° turn @ 3-4g **Mark:** ________________
-Start at 400 KCAS
-Hold Alt at 8K ft PA/ Level
-Power at 93%
-Airspeed will bleed

A2. 90° turn @ 4-5g **Mark:** ________________
-Start at 450 KCAS
-Hold Alt at 8K ft PA/ Level
-Power at 93%
-Airspeed will bleed

B. Level 360° Turn **Mark:** ________________
-450 KCAS / 5g / Power as Req'd (~93%)
-Hold Alt at 8K ft PA

Ops Check: __________ 4



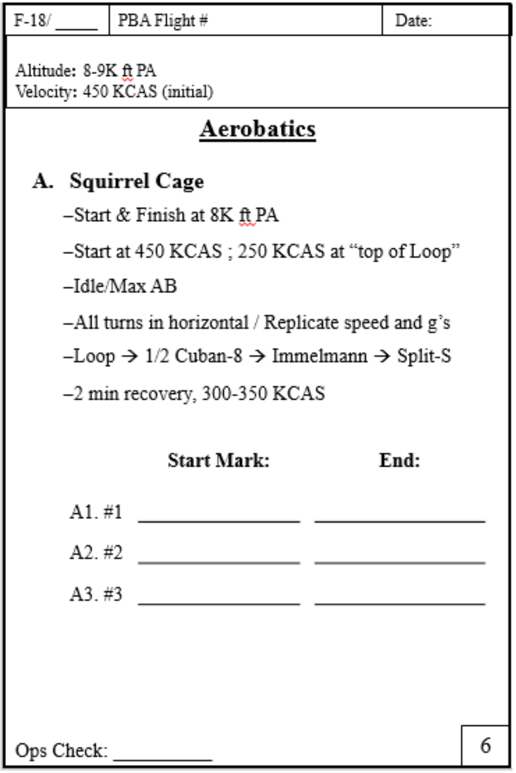
F-18/ ____	PBA Flight #	Date:

Altitude: 8K ft PA
Velocity: 300-400 KCAS, Straight and Level, Unaccelerated

8000 ft Cabin/Pressure Altitude - Continued

C. Check-6 Assessment **Mark:** ________________
–Clear forward as needed
–300-400 KCAS / Hold constant airspeed
–Hold constant Altitude
–Look LEFT for 30 secs
–Look RIGHT for 30 secs

Ops Check: __________ 5



F-18/ ____	PBA Flight #	Date:

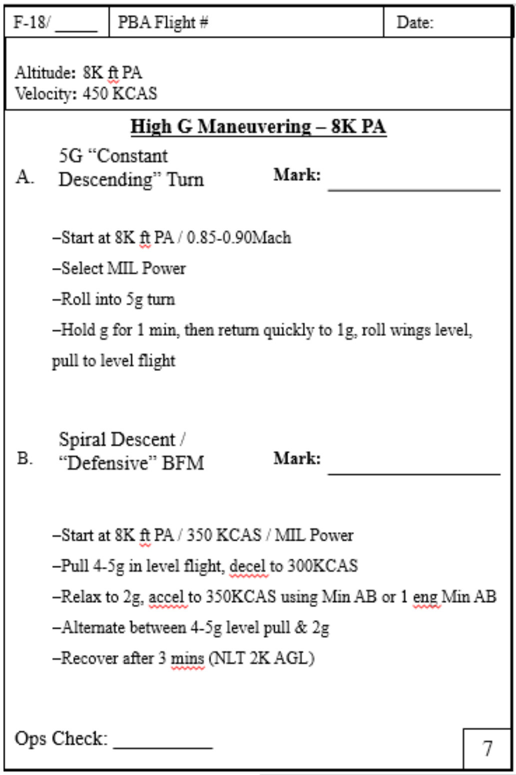
Altitude: 8-9K ft PA
Velocity: 450 KCAS (initial)

Aerobatics

A. Squirrel Cage
–Start & Finish at 8K ft PA
–Start at 450 KCAS ; 250 KCAS at "top of Loop"
–Idle/Max AB
–All turns in horizontal / Replicate speed and g's
–Loop → 1/2 Cuban-8 → Immelmann → Split-S
–2 min recovery, 300-350 KCAS

	Start Mark:	**End:**
A1. #1	________________	________________
A2. #2	________________	________________
A3. #3	________________	________________

Ops Check: __________ 6



F-18/ _____	PBA Flight #	Date:

Altitude: 8K ft PA
Velocity: 450 KCAS

High G Maneuvering – 8K PA

A. 5G "Constant Descending" Turn **Mark:** ________________

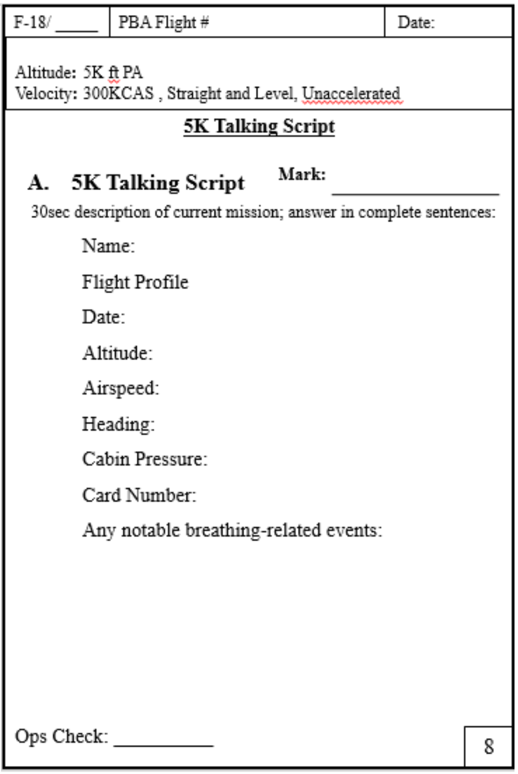
–Start at 8K ft PA / 0.85-0.90Mach
–Select MIL Power
–Roll into 5g turn
–Hold g for 1 min, then return quickly to 1g, roll wings level, pull to level flight

B. Spiral Descent / "Defensive" BFM **Mark:** ________________

–Start at 8K ft PA / 350 KCAS / MIL Power
–Pull 4-5g in level flight, decel to 300KCAS
–Relax to 2g, accel to 350KCAS using Min AB or 1 eng Min AB
–Alternate between 4-5g level pull & 2g
–Recover after 3 mins (NLT 2K AGL)

Ops Check: __________

7



F-18/ _____	PBA Flight #	Date:

Altitude: 5K ft PA
Velocity: 300KCAS , Straight and Level, Unaccelerated

5K Talking Script

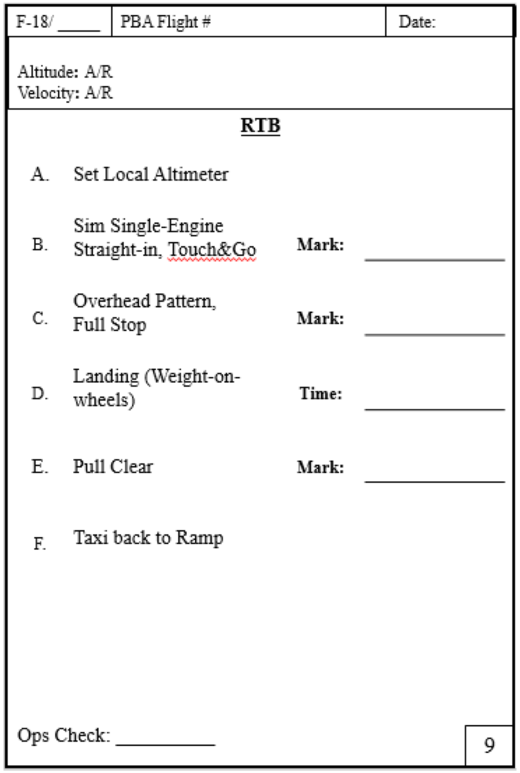
A. 5K Talking Script **Mark:** ________________

30sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

8



F-18/ _____	PBA Flight #	Date:

Altitude: A/R
Velocity: A/R

RTB

A. Set Local Altimeter

B. Sim Single-Engine Straight-in, Touch&Go **Mark:** ______________

C. Overhead Pattern, Full Stop **Mark:** ______________

D. Landing (Weight-on-wheels) **Time:** ______________

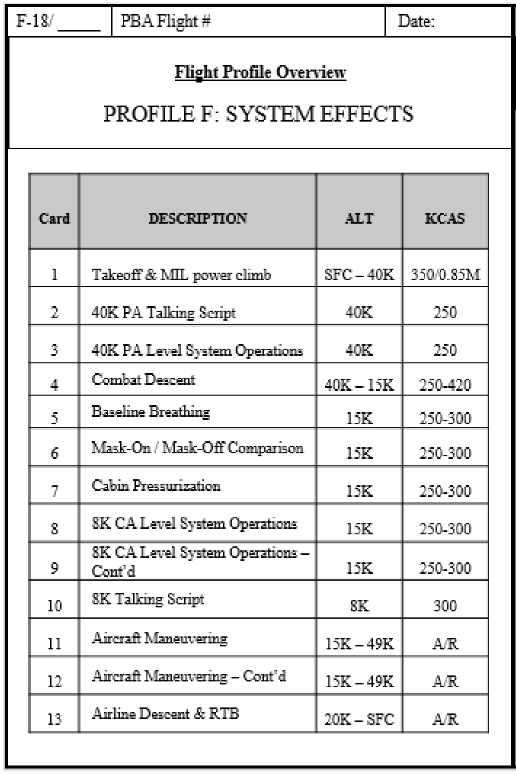
E. Pull Clear **Mark:** ______________

F. Taxi back to Ramp

Ops Check: __________

9

Profile F: Functional Check Flight

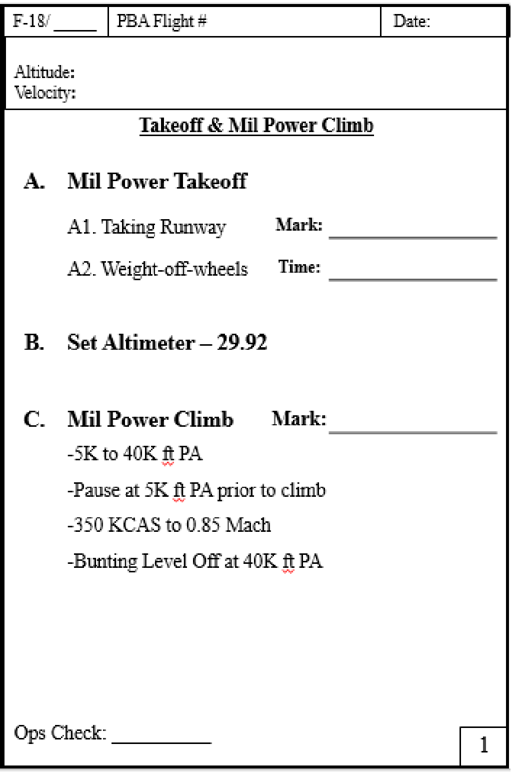


F-18/ _____	PBA Flight #	Date:

Flight Profile Overview

PROFILE F: SYSTEM EFFECTS

Card	DESCRIPTION	ALT	KCAS
1	Takeoff & MIL power climb	SFC – 40K	350/0.85M
2	40K PA Talking Script	40K	250
3	40K PA Level System Operations	40K	250
4	Combat Descent	40K – 15K	250-420
5	Baseline Breathing	15K	250-300
6	Mask-On / Mask-Off Comparison	15K	250-300
7	Cabin Pressurization	15K	250-300
8	8K CA Level System Operations	15K	250-300
9	8K CA Level System Operations – Cont'd	15K	250-300
10	8K Talking Script	8K	300
11	Aircraft Maneuvering	15K – 49K	A/R
12	Aircraft Maneuvering – Cont'd	15K – 49K	A/R
13	Airline Descent & RTB	20K – SFC	A/R



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

Takeoff & Mil Power Climb

A. Mil Power Takeoff

A1. Taking Runway **Mark:** _______________

A2. Weight-off-wheels **Time:** _______________

B. Set Altimeter – 29.92

C. Mil Power Climb **Mark:** _______________

-5K to 40K ft PA

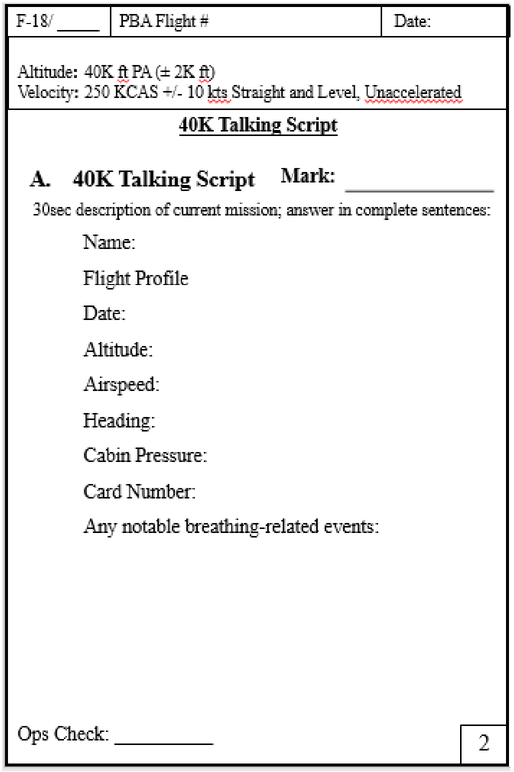
-Pause at 5K ft PA prior to climb

-350 KCAS to 0.85 Mach

-Bunting Level Off at 40K ft PA

Ops Check: __________

1



F-18/ _____	PBA Flight #	Date:

Altitude: 40K ft PA (± 2K ft)
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

40K Talking Script

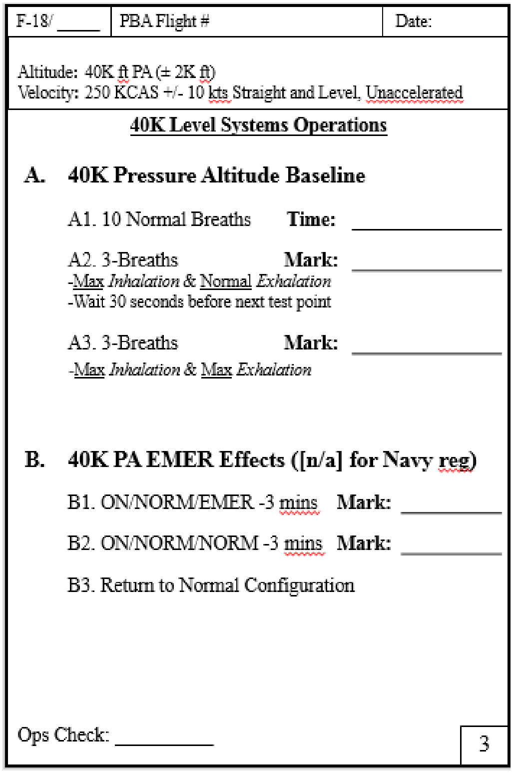
A. 40K Talking Script **Mark:** _______________

30sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

2



F-18/ ____	PBA Flight #	Date:

Altitude: 40K ft PA (± 2K ft)
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

40K Level Systems Operations

A. 40K Pressure Altitude Baseline

A1. 10 Normal Breaths **Time:** ________

A2. 3-Breaths **Mark:** ________
-Max *Inhalation* & Normal *Exhalation*
-Wait 30 seconds before next test point

A3. 3-Breaths **Mark:** ________
-Max *Inhalation* & Max *Exhalation*

B. 40K PA EMER Effects ([n/a] for Navy reg)

B1. ON/NORM/EMER -3 mins **Mark:** ________

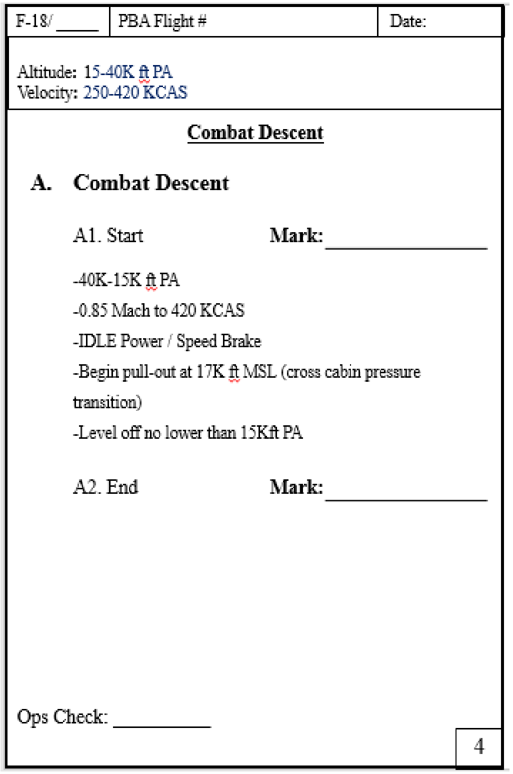
B2. ON/NORM/NORM -3 mins **Mark:** ________

B3. Return to Normal Configuration

Ops Check: ________

3

A. Qualitative Baseline
    A. For Pilot Self Assessment of what it takes for 10 normal breaths
B. Max Inhalation
    A. Deep Inhale, as deep as possible
C. Normal Exhalation
    A. Do not exaggerate exhale
D. Max Exhalation
    A. Complete a Deep Breath
    B. Much like spirometry, but without the wretching
    C. Want to see maximum supply need
    D. Want to see changes in O2
    E. Force, Pressure, and Flow



F-18/ ____	PBA Flight #	Date:

Altitude: 15-40K ft PA
Velocity: 250-420 KCAS

Combat Descent

A. Combat Descent

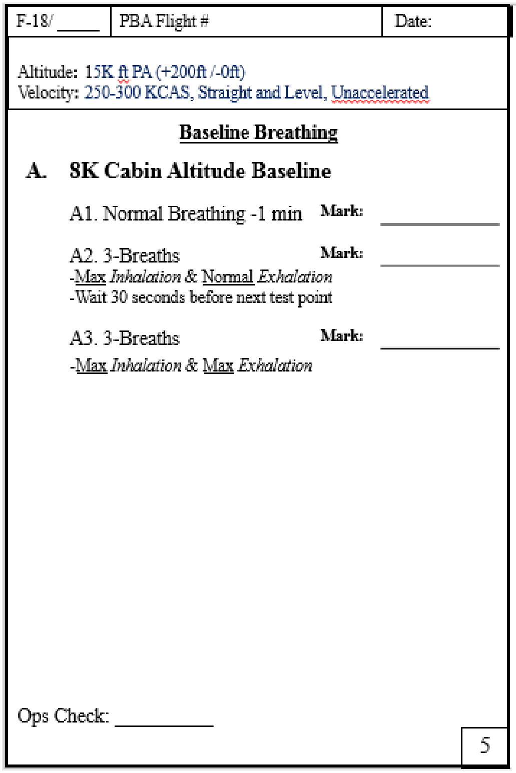
A1. Start **Mark:** ________

-40K-15K ft PA
-0.85 Mach to 420 KCAS
-IDLE Power / Speed Brake
-Begin pull-out at 17K ft MSL (cross cabin pressure transition)
-Level off no lower than 15Kft PA

A2. End **Mark:** ________

Ops Check: ________

4



F-18/ ____ PBA Flight # Date:

Altitude: 15K ft PA (+200ft /-0ft)
Velocity: 250-300 KCAS, Straight and Level, Unaccelerated

Baseline Breathing

A. 8K Cabin Altitude Baseline

A1. Normal Breathing -1 min **Mark:** ________

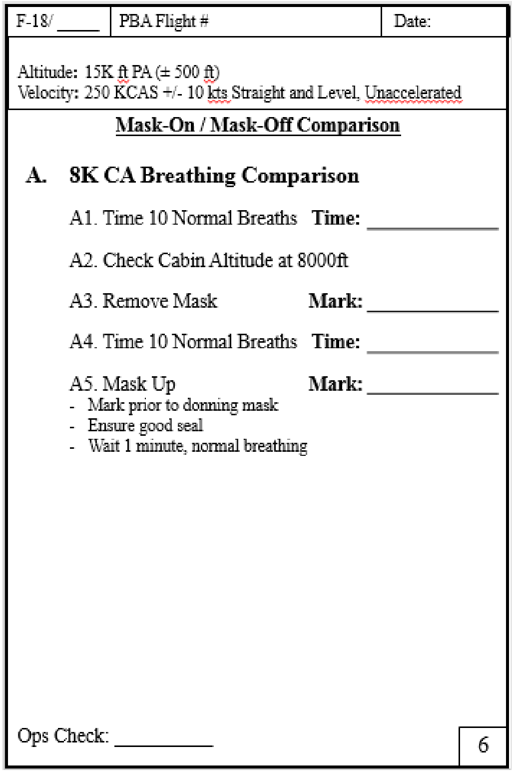
A2. 3-Breaths **Mark:** ________
-Max *Inhalation* & Normal *Exhalation*
-Wait 30 seconds before next test point

A3. 3-Breaths **Mark:** ________
-Max *Inhalation* & Max *Exhalation*

Ops Check: ________

5

A. Qualitative Baseline
    A. For Pilot Self Assessment of what it takes for 10 normal breaths
B. Max Inhalation
    A. Deep Inhale, as deep as possible
C. Normal Exhalation
    A. Do not exaggerate exhale
D. Max Exhalation
    A. Complete a Deep Breath
    B. Much like spirometry, but without the wretching
    C. Want to see maximum supply need
    D. Want to see changes in O2
    E. Force, Pressure, and Flow



F-18/ ____ PBA Flight # Date:

Altitude: 15K ft PA (± 500 ft)
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

Mask-On / Mask-Off Comparison

A. 8K CA Breathing Comparison

A1. Time 10 Normal Breaths **Time:** ________

A2. Check Cabin Altitude at 8000ft

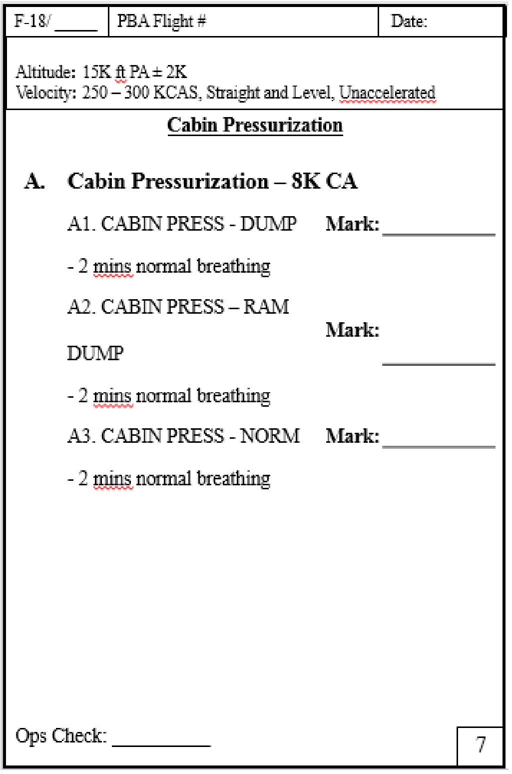
A3. Remove Mask **Mark:** ________

A4. Time 10 Normal Breaths **Time:** ________

A5. Mask Up **Mark:** ________
- Mark prior to donning mask
- Ensure good seal
- Wait 1 minute, normal breathing

Ops Check: ________

6



F-18/ ____ PBA Flight # Date:

Altitude: 15K ft PA ± 2K
Velocity: 250 – 300 KCAS, Straight and Level, Unaccelerated

Cabin Pressurization

A. Cabin Pressurization – 8K CA

A1. CABIN PRESS - DUMP **Mark:** ________

- 2 mins normal breathing

A2. CABIN PRESS – RAM DUMP **Mark:** ________

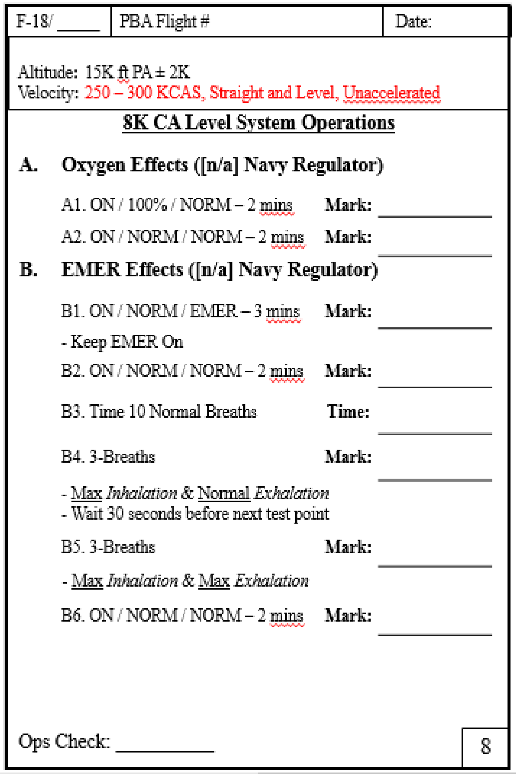
- 2 mins normal breathing

A3. CABIN PRESS - NORM **Mark:** ________

- 2 mins normal breathing

Ops Check: ________

7



F-18/ ____	PBA Flight #	Date:

Altitude: 15K ft PA ± 2K
Velocity: 250 – 300 KCAS, Straight and Level, Unaccelerated

8K CA Level System Operations

A. Oxygen Effects ([n/a] Navy Regulator)

A1. ON / 100% / NORM – 2 mins **Mark:** ________

A2. ON / NORM / NORM – 2 mins **Mark:** ________

B. EMER Effects ([n/a] Navy Regulator)

B1. ON / NORM / EMER – 3 mins **Mark:** ________

- Keep EMER On

B2. ON / NORM / NORM – 2 mins **Mark:** ________

B3. Time 10 Normal Breaths **Time:** ________

B4. 3-Breaths **Mark:** ________

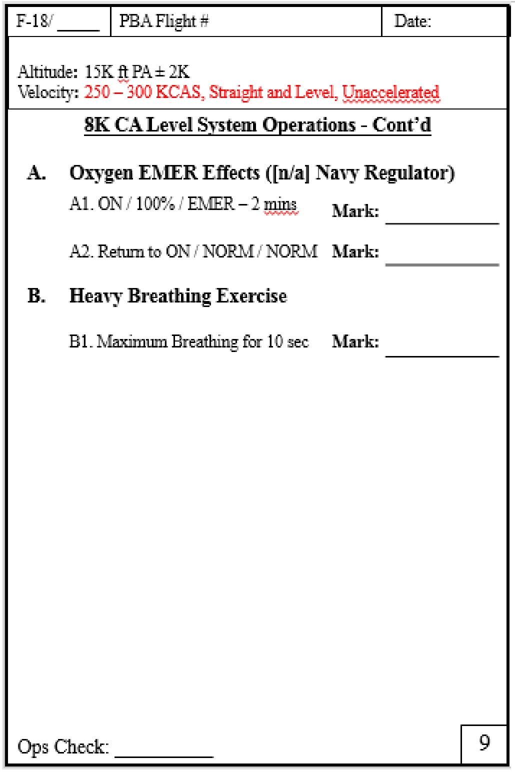
- *Max Inhalation & Normal Exhalation*
- Wait 30 seconds before next test point

B5. 3-Breaths **Mark:** ________

- *Max Inhalation & Max Exhalation*

B6. ON / NORM / NORM – 2 mins **Mark:** ________

Ops Check: ________ 8



F-18/ ____	PBA Flight #	Date:

Altitude: 15K ft PA ± 2K
Velocity: 250 – 300 KCAS, Straight and Level, Unaccelerated

8K CA Level System Operations - Cont'd

A. Oxygen EMER Effects ([n/a] Navy Regulator)

A1. ON / 100% / EMER – 2 mins **Mark:** ________

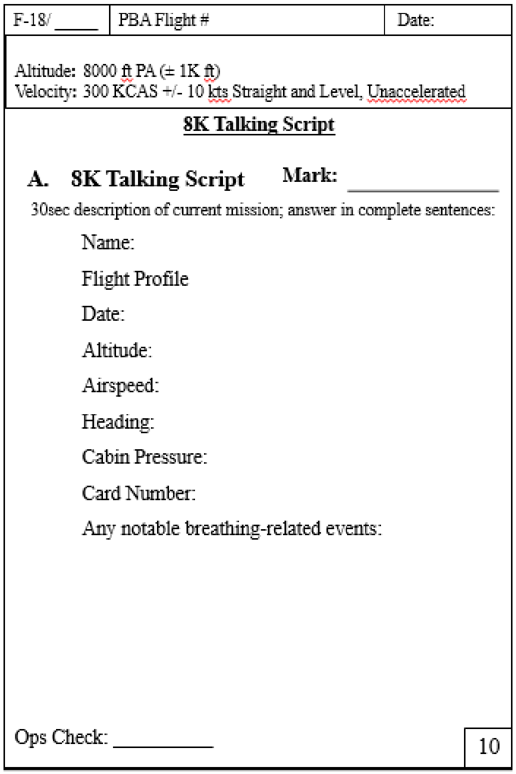
A2. Return to ON / NORM / NORM **Mark:** ________

B. Heavy Breathing Exercise

B1. Maximum Breathing for 10 sec **Mark:** ________

Ops Check: ________ 9

A. Maximum Breathing
   I. Max open mouth breathing
   II. Approximately 6-9 breaths
   III. 10 secs maximum
   IV. "challenge the system at high volume over time"
   V. Larger rates of change and quicker flows
   VI. "catching your breath after sprinting/climbing stairs"



F-18/ _____	PBA Flight #	Date:

Altitude: 8000 ft PA (± 1K ft)
Velocity: 300 KCAS +/- 10 kts Straight and Level, Unaccelerated

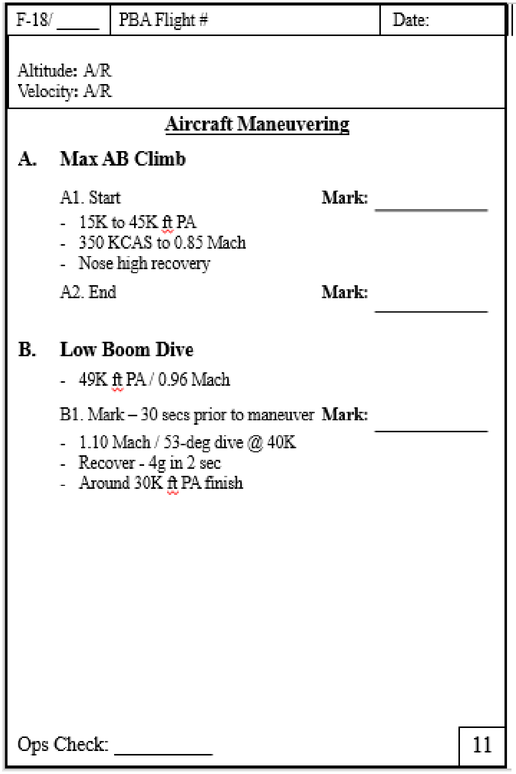
8K Talking Script

A. 8K Talking Script **Mark:** ______________

30sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________ 10



F-18/ _____	PBA Flight #	Date:

Altitude: A/R
Velocity: A/R

Aircraft Maneuvering

A. Max AB Climb

A1. Start **Mark:** ___________
- 15K to 45K ft PA
- 350 KCAS to 0.85 Mach
- Nose high recovery

A2. End **Mark:** ___________

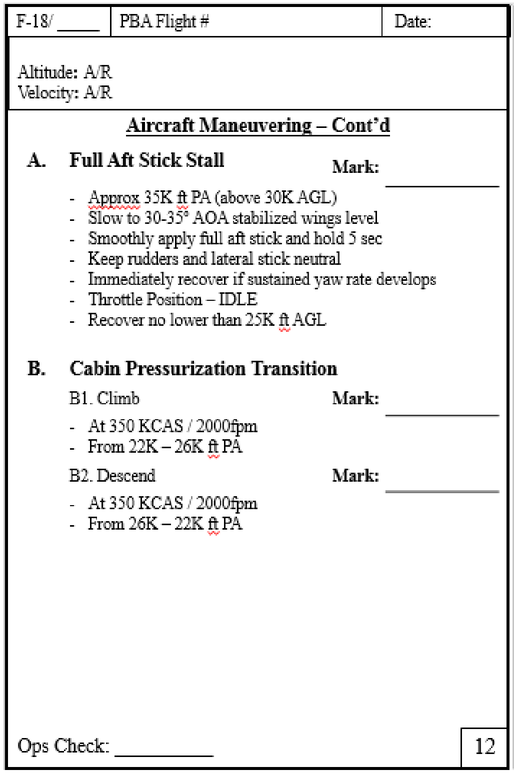
B. Low Boom Dive
- 49K ft PA / 0.96 Mach

B1. Mark – 30 secs prior to maneuver **Mark:** ___________
- 1.10 Mach / 53-deg dive @ 40K
- Recover - 4g in 2 sec
- Around 30K ft PA finish

Ops Check: __________ 11

Ops 5.7 needed

A. Purpose
    A. To stress cabin transition
    B. Done late in profile to allow for lighter jet / faster transit



F-18/ _____	PBA Flight #	Date:

Altitude: A/R
Velocity: A/R

Aircraft Maneuvering – Cont'd

A. Full Aft Stick Stall **Mark:** ____________

- Approx 35K ft PA (above 30K AGL)
- Slow to 30-35° AOA stabilized wings level
- Smoothly apply full aft stick and hold 5 sec
- Keep rudders and lateral stick neutral
- Immediately recover if sustained yaw rate develops
- Throttle Position – IDLE
- Recover no lower than 25K ft AGL

B. Cabin Pressurization Transition

B1. Climb **Mark:** ____________

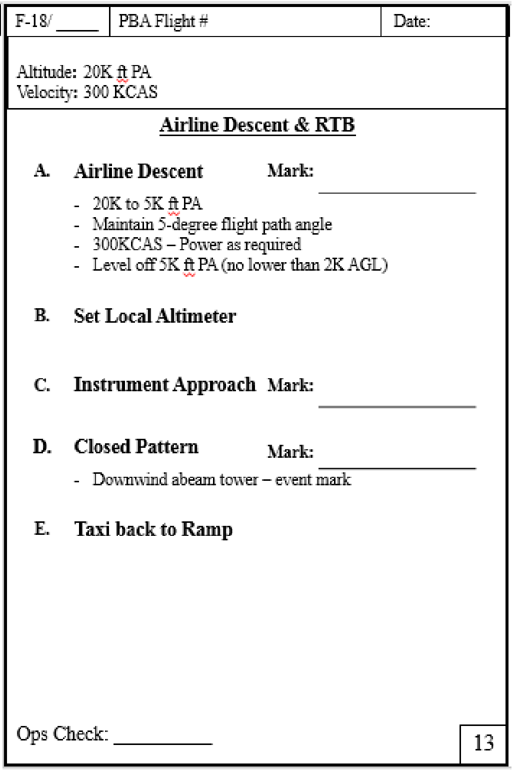
- At 350 KCAS / 2000fpm
- From 22K – 26K ft PA

B2. Descend **Mark:** ____________

- At 350 KCAS / 2000fpm
- From 26K – 22K ft PA

Ops Check: __________

12



F-18/ _____	PBA Flight #	Date:

Altitude: 20K ft PA
Velocity: 300 KCAS

Airline Descent & RTB

A. Airline Descent **Mark:** ____________

- 20K to 5K ft PA
- Maintain 5-degree flight path angle
- 300KCAS – Power as required
- Level off 5K ft PA (no lower than 2K AGL)

B. Set Local Altimeter

C. Instrument Approach **Mark:** ____________

D. Closed Pattern **Mark:** ____________

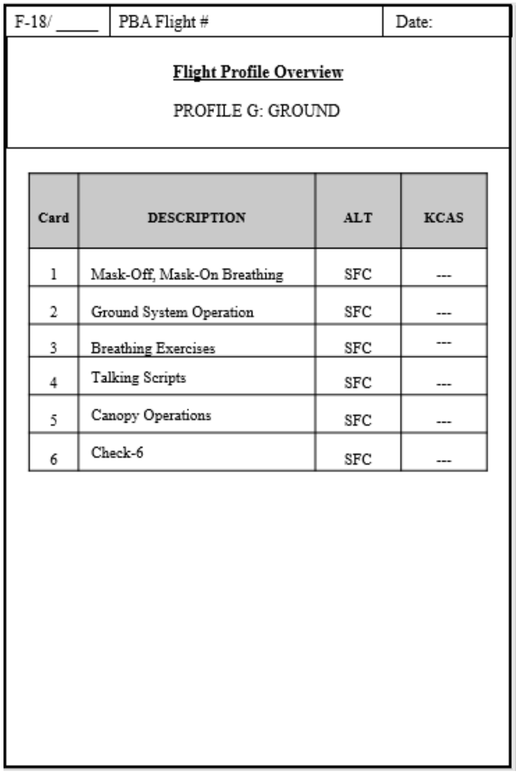
- Downwind abeam tower – event mark

E. Taxi back to Ramp

Ops Check: __________

13

Profile G: Ground only

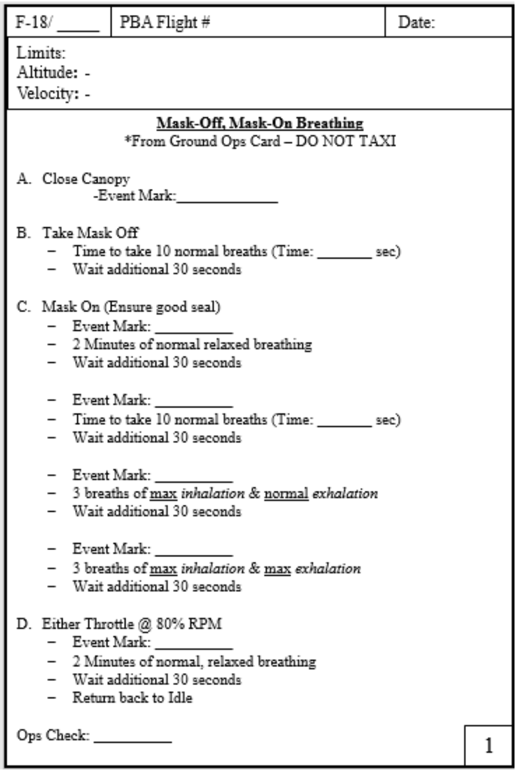


F-18/ _____	PBA Flight #	Date:

Flight Profile Overview

PROFILE G: GROUND

Card	DESCRIPTION	ALT	KCAS
1	Mask-Off, Mask-On Breathing	SFC	---
2	Ground System Operation	SFC	---
3	Breathing Exercises	SFC	---
4	Talking Scripts	SFC	---
5	Canopy Operations	SFC	---
6	Check-6	SFC	---



F-18/ _____	PBA Flight #	Date:

Limits:
Altitude: -
Velocity: -

Mask-Off, Mask-On Breathing
*From Ground Ops Card – DO NOT TAXI

A. Close Canopy
-Event Mark:____________

B. Take Mask Off
- Time to take 10 normal breaths (Time: _______ sec)
- Wait additional 30 seconds

C. Mask On (Ensure good seal)
- Event Mark: _________
- 2 Minutes of normal relaxed breathing
- Wait additional 30 seconds

- Event Mark: _________
- Time to take 10 normal breaths (Time: _______ sec)
- Wait additional 30 seconds

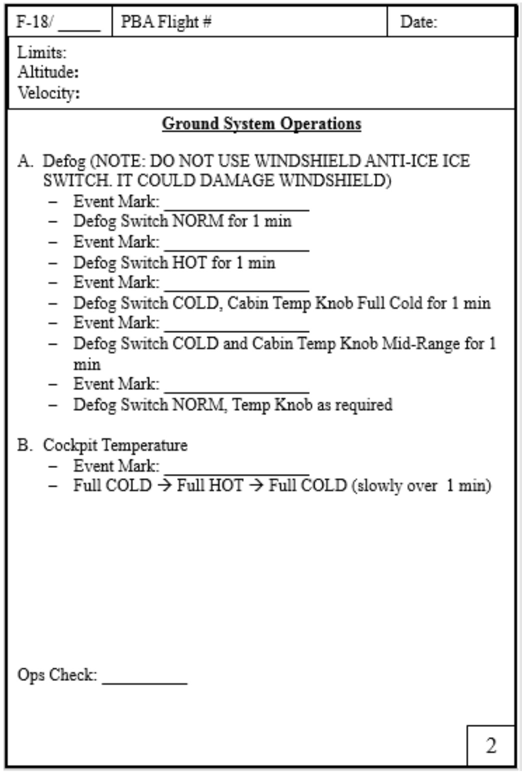
- Event Mark: _________
- 3 breaths of max *inhalation* & normal *exhalation*
- Wait additional 30 seconds

- Event Mark: _________
- 3 breaths of max *inhalation* & max *exhalation*
- Wait additional 30 seconds

D. Either Throttle @ 80% RPM
- Event Mark: _________
- 2 Minutes of normal, relaxed breathing
- Wait additional 30 seconds
- Return back to Idle

Ops Check: _________

1



F-18/ _____	PBA Flight #	Date:

Limits:
Altitude:
Velocity:

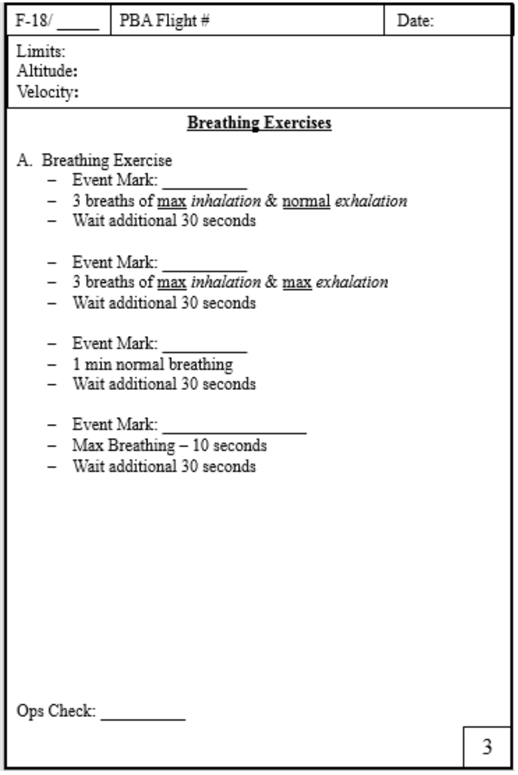
Ground System Operations

A. Defog (NOTE: DO NOT USE WINDSHIELD ANTI-ICE ICE SWITCH. IT COULD DAMAGE WINDSHIELD)
- Event Mark: _______________
- Defog Switch NORM for 1 min
- Event Mark: _______________
- Defog Switch HOT for 1 min
- Event Mark: _______________
- Defog Switch COLD, Cabin Temp Knob Full Cold for 1 min
- Event Mark: _______________
- Defog Switch COLD and Cabin Temp Knob Mid-Range for 1 min
- Event Mark: _______________
- Defog Switch NORM, Temp Knob as required

B. Cockpit Temperature
- Event Mark: _______________
- Full COLD → Full HOT → Full COLD (slowly over 1 min)

Ops Check: _________

2



F-18/ _____	PBA Flight #	Date:

Limits:
Altitude:
Velocity:

Breathing Exercises

A. Breathing Exercise
- Event Mark: _________
- 3 breaths of max *inhalation* & normal *exhalation*
- Wait additional 30 seconds

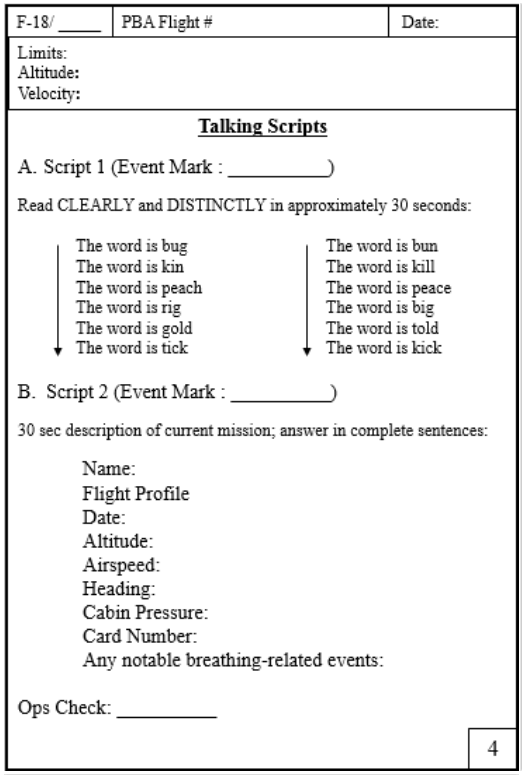
- Event Mark: _________
- 3 breaths of max *inhalation* & max *exhalation*
- Wait additional 30 seconds

- Event Mark: _________
- 1 min normal breathing
- Wait additional 30 seconds

- Event Mark: _______________
- Max Breathing – 10 seconds
- Wait additional 30 seconds

Ops Check: _________

3



F-18/ _____	PBA Flight #	Date:

Limits:
Altitude:
Velocity:

Talking Scripts

A. Script 1 (Event Mark : __________)

Read CLEARLY and DISTINCTLY in approximately 30 seconds:

The word is bug
The word is kin
The word is peach
The word is rig
The word is gold
The word is tick

The word is bun
The word is kill
The word is peace
The word is big
The word is told
The word is kick

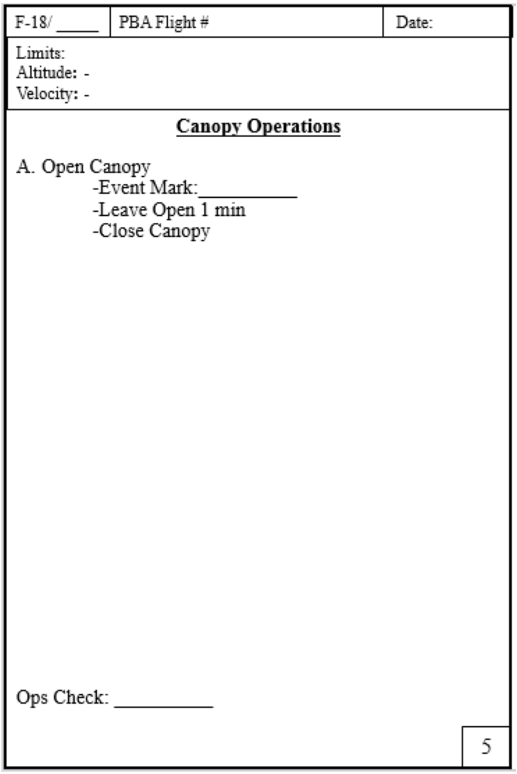
B. Script 2 (Event Mark : __________)

30 sec description of current mission; answer in complete sentences:

Name:
Flight Profile
Date:
Altitude:
Airspeed:
Heading:
Cabin Pressure:
Card Number:
Any notable breathing-related events:

Ops Check: __________

4



F-18/ _____	PBA Flight #	Date:

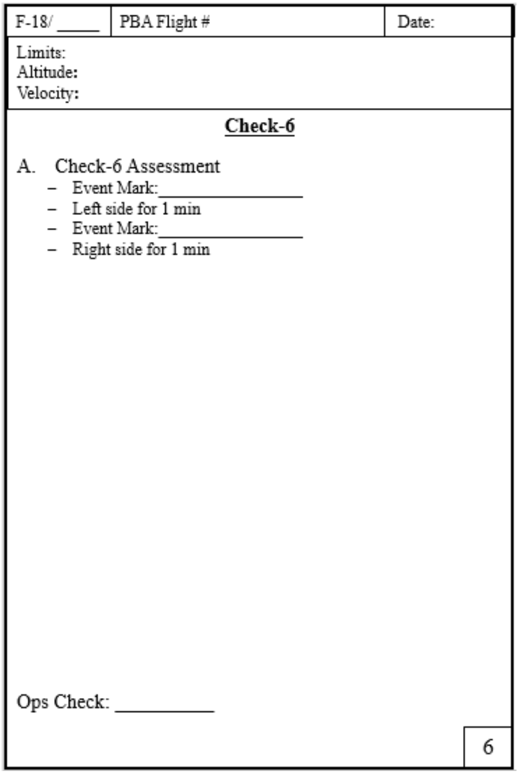
Limits:
Altitude: -
Velocity: -

Canopy Operations

A. Open Canopy
-Event Mark:__________
-Leave Open 1 min
-Close Canopy

Ops Check: __________

5



F-18/ _____	PBA Flight #	Date:

Limits:
Altitude:
Velocity:

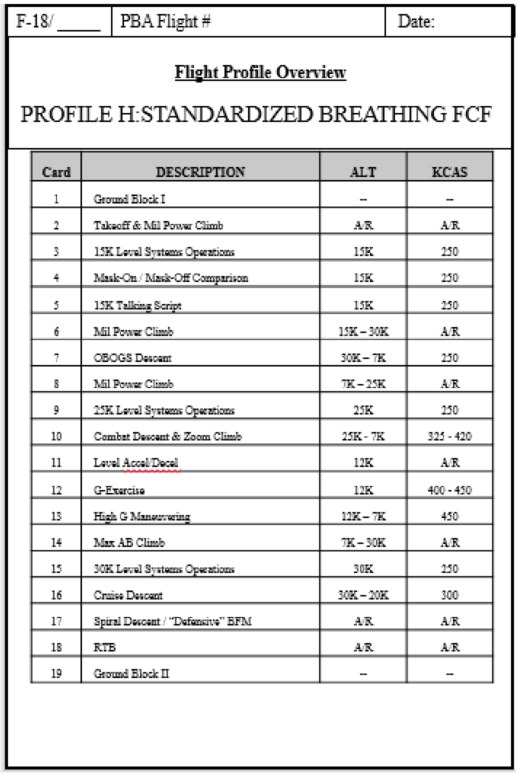
Check-6

A. Check-6 Assessment
- Event Mark:_______________
- Left side for 1 min
- Event Mark:_______________
- Right side for 1 min

Ops Check: __________

6

Profile H: Health Check – Standardized Flight Test Profile

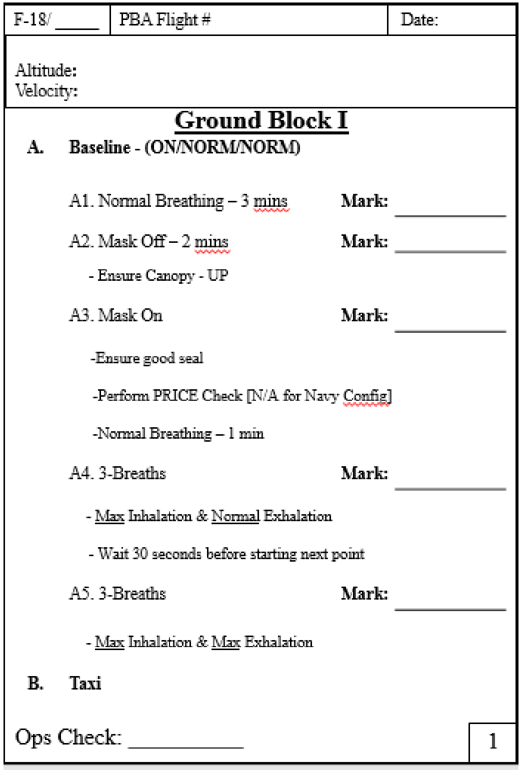


F-18/ _____	PBA Flight #	Date:

Flight Profile Overview

PROFILE H:STANDARDIZED BREATHING FCF

Card	DESCRIPTION	ALT	KCAS
1	Ground Block I	--	--
2	Takeoff & Mil Power Climb	A/R	A/R
3	15K Level Systems Operations	15K	250
4	Mask-On / Mask-Off Comparison	15K	250
5	15K Talking Script	15K	250
6	Mil Power Climb	15K – 30K	A/R
7	OBOGS Descent	30K – 7K	250
8	Mil Power Climb	7K – 25K	A/R
9	25K Level Systems Operations	25K	250
10	Combat Descent & Zoom Climb	25K - 7K	325 - 420
11	Level Accel/Decel	12K	A/R
12	G-Exercise	12K	400 - 450
13	High G Maneuvering	12K – 7K	450
14	Max AB Climb	7K – 30K	A/R
15	30K Level Systems Operations	30K	250
16	Cruise Descent	30K – 20K	300
17	Spiral Descent / "Defensive" BFM	A/R	A/R
18	RTB	A/R	A/R
19	Ground Block II	--	--



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

Ground Block I

A. Baseline - (ON/NORM/NORM)

A1. Normal Breathing – 3 mins **Mark:** ____________

A2. Mask Off – 2 mins **Mark:** ____________

- Ensure Canopy - UP

A3. Mask On **Mark:** ____________

-Ensure good seal

-Perform PRICE Check [N/A for Navy Config]

-Normal Breathing – 1 min

A4. 3-Breaths **Mark:** ____________

- Max Inhalation & Normal Exhalation

- Wait 30 seconds before starting next point

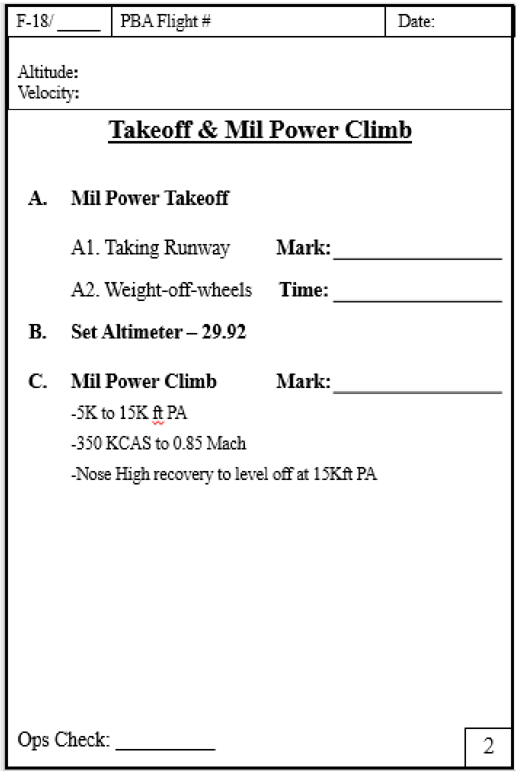
A5. 3-Breaths **Mark:** ____________

- Max Inhalation & Max Exhalation

B. Taxi

Ops Check: ___________

1



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

Takeoff & Mil Power Climb

A. Mil Power Takeoff

A1. Taking Runway **Mark:** ________________

A2. Weight-off-wheels **Time:** ________________

B. Set Altimeter – 29.92

C. Mil Power Climb **Mark:** ________________

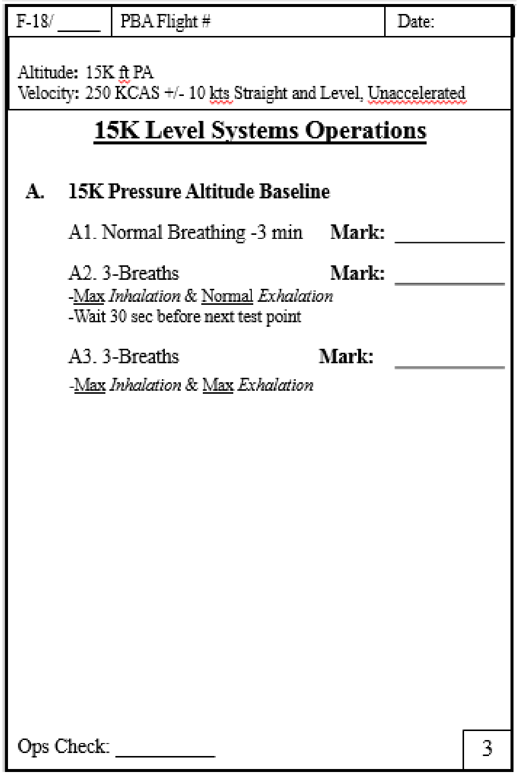
-5K to 15K ft PA

-350 KCAS to 0.85 Mach

-Nose High recovery to level off at 15Kft PA

Ops Check: __________

2



F-18/ _____	PBA Flight #	Date:

Altitude: 15K ft PA
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

15K Level Systems Operations

A. 15K Pressure Altitude Baseline

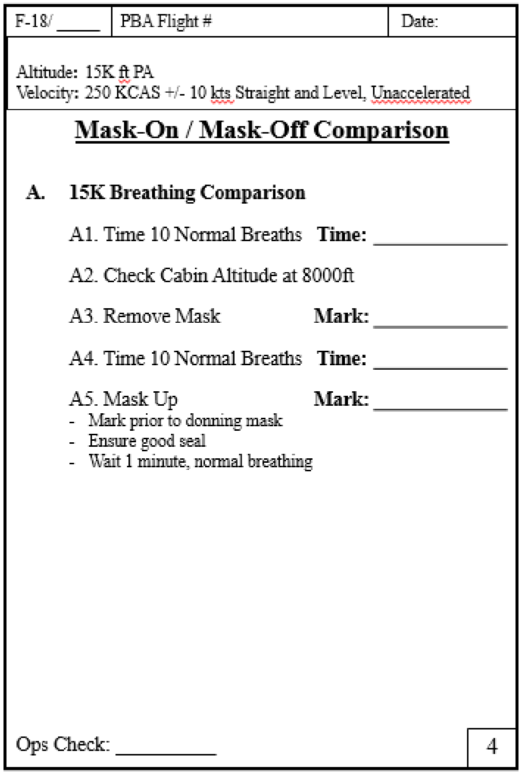
A1. Normal Breathing -3 min **Mark:** ___________

A2. 3-Breaths **Mark:** ___________
-Max *Inhalation* & Normal *Exhalation*
-Wait 30 sec before next test point

A3. 3-Breaths **Mark:** ___________
-Max *Inhalation* & Max *Exhalation*

Ops Check: __________

3



F-18/ _____	PBA Flight #	Date:

Altitude: 15K ft PA
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

Mask-On / Mask-Off Comparison

A. 15K Breathing Comparison

A1. Time 10 Normal Breaths **Time:** ____________

A2. Check Cabin Altitude at 8000ft

A3. Remove Mask **Mark:** ____________

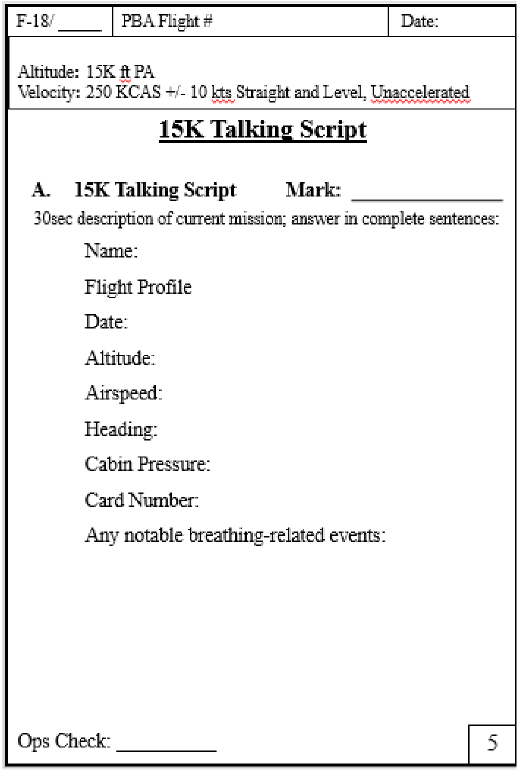
A4. Time 10 Normal Breaths **Time:** ____________

A5. Mask Up **Mark:** ____________

- Mark prior to donning mask
- Ensure good seal
- Wait 1 minute, normal breathing

Ops Check: _________

4



F-18/ _____	PBA Flight #	Date:

Altitude: 15K ft PA
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

15K Talking Script

A. 15K Talking Script **Mark:** ____________

30sec description of current mission; answer in complete sentences:

Name:

Flight Profile

Date:

Altitude:

Airspeed:

Heading:

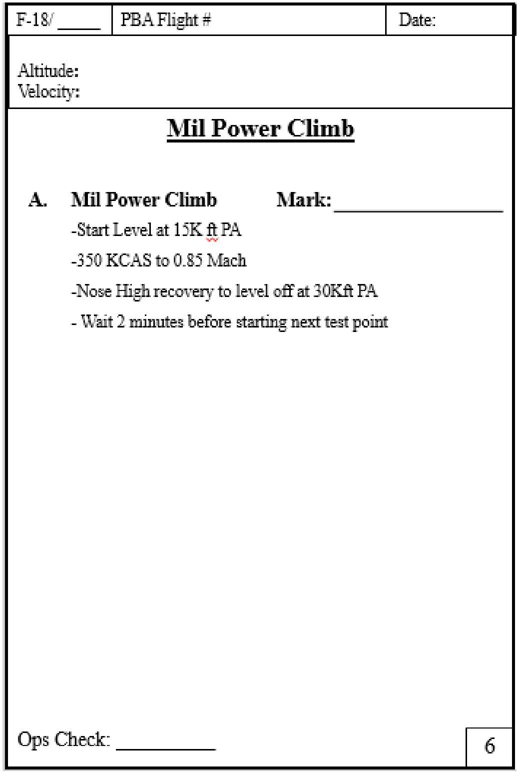
Cabin Pressure:

Card Number:

Any notable breathing-related events:

Ops Check: _________

5



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity:

Mil Power Climb

A. Mil Power Climb **Mark:** ______________

-Start Level at 15K ft PA

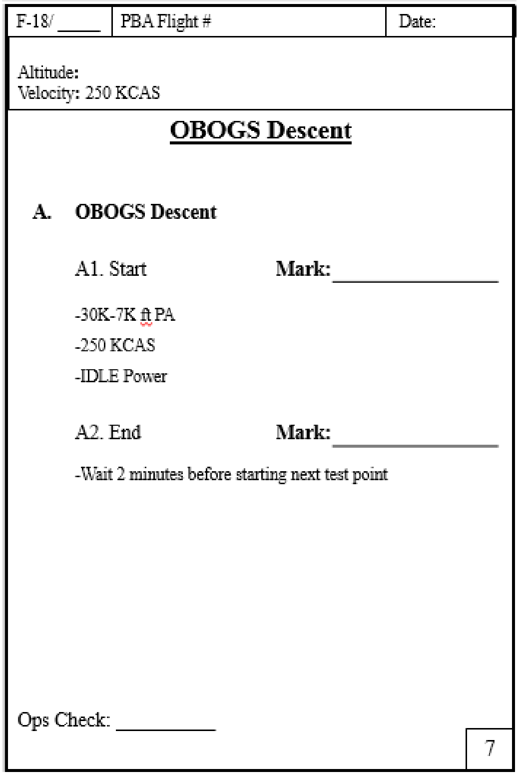
-350 KCAS to 0.85 Mach

-Nose High recovery to level off at 30Kft PA

- Wait 2 minutes before starting next test point

Ops Check: _________

6



F-18/ _____	PBA Flight #	Date:

Altitude:
Velocity: 250 KCAS

OBOGS Descent

A. OBOGS Descent

A1. Start **Mark:** ______________

-30K-7K ft PA

-250 KCAS

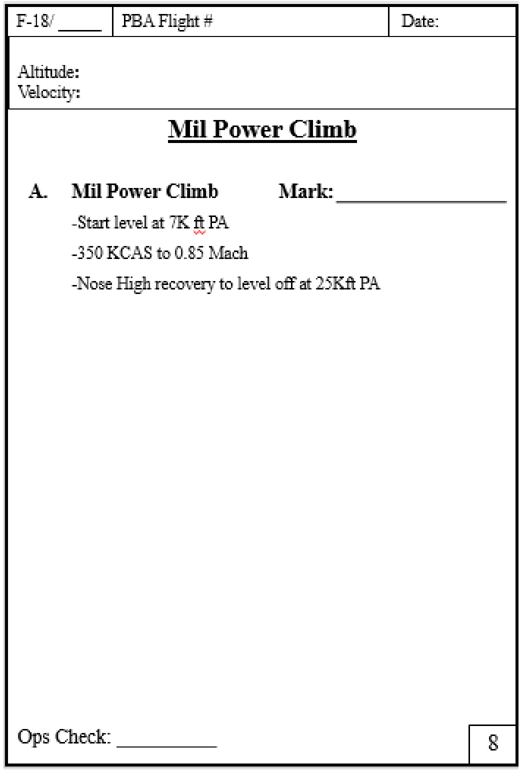
-IDLE Power

A2. End **Mark:** ______________

-Wait 2 minutes before starting next test point

Ops Check: _________

7



F-18/ ____	PBA Flight #	Date:

Altitude:
Velocity:

Mil Power Climb

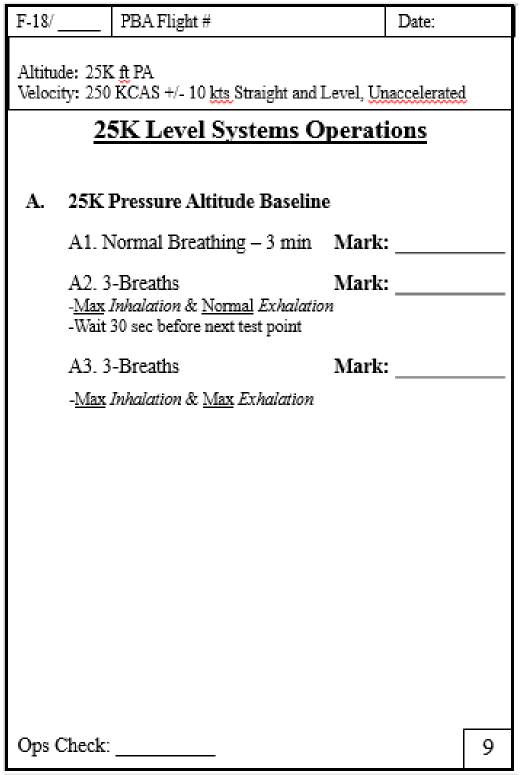
A. Mil Power Climb **Mark:** ______________

-Start level at 7K ft PA

-350 KCAS to 0.85 Mach

-Nose High recovery to level off at 25Kft PA

Ops Check: _________ 8



F-18/ ____	PBA Flight #	Date:

Altitude: 25K ft PA
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

25K Level Systems Operations

A. 25K Pressure Altitude Baseline

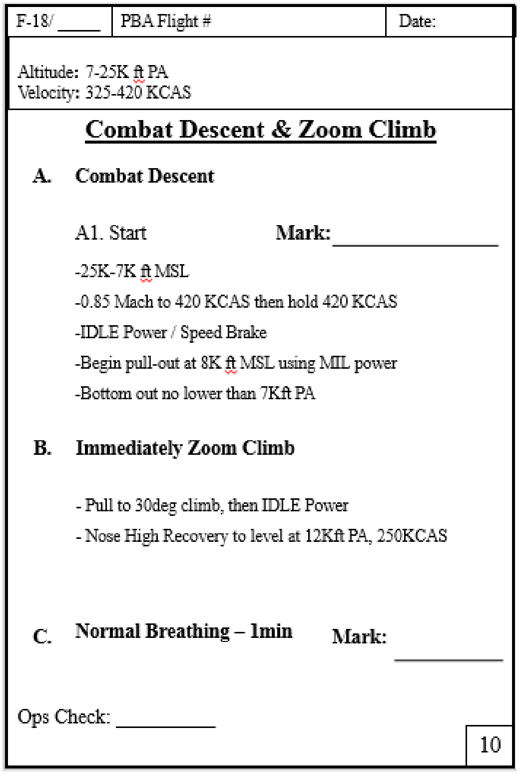
A1. Normal Breathing – 3 min **Mark:** __________

A2. 3-Breaths **Mark:** __________
-Max *Inhalation* & Normal *Exhalation*
-Wait 30 sec before next test point

A3. 3-Breaths **Mark:** __________

-Max *Inhalation* & Max *Exhalation*

Ops Check: _________ 9



F-18/ ____	PBA Flight #	Date:

Altitude: 7-25K ft PA
Velocity: 325-420 KCAS

Combat Descent & Zoom Climb

A. Combat Descent

A1. Start **Mark:** ______________

-25K-7K ft MSL

-0.85 Mach to 420 KCAS then hold 420 KCAS

-IDLE Power / Speed Brake

-Begin pull-out at 8K ft MSL using MIL power

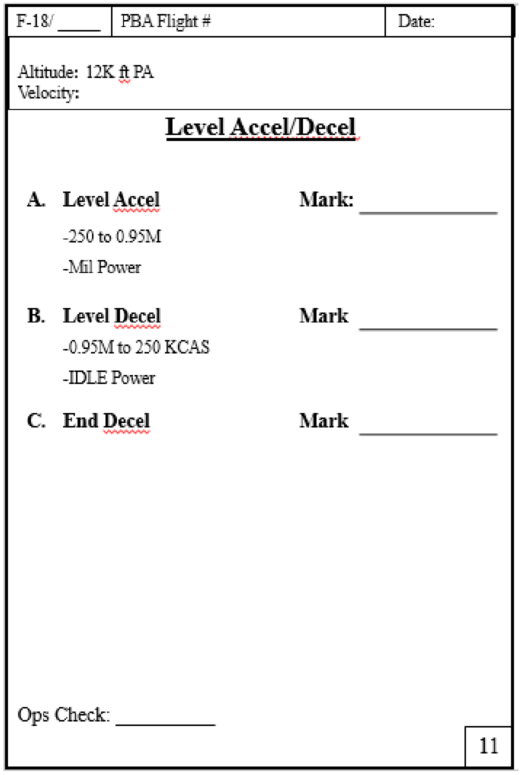
-Bottom out no lower than 7Kft PA

B. Immediately Zoom Climb

- Pull to 30deg climb, then IDLE Power
- Nose High Recovery to level at 12Kft PA, 250KCAS

C. Normal Breathing – 1min **Mark:** __________

Ops Check: _________ 10



F-18/ ____	PBA Flight #	Date:

Altitude: 12K ft PA
Velocity:

Level Accel/Decel

A. Level Accel **Mark:** ____________

-250 to 0.95M

-Mil Power

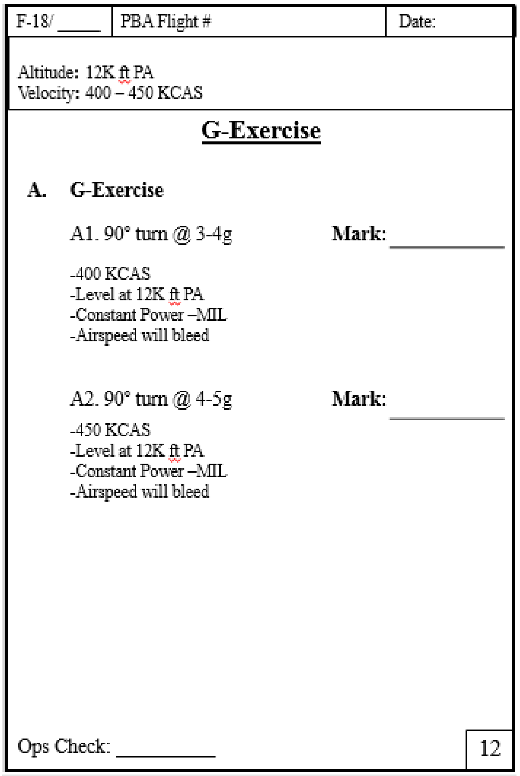
B. Level Decel **Mark** ____________

-0.95M to 250 KCAS

-IDLE Power

C. End Decel **Mark** ____________

Ops Check: _________ 11



F-18/ _____ | PBA Flight # | Date:

Altitude: 12K ft PA
Velocity: 400 – 450 KCAS

G-Exercise

A. G-Exercise

A1. 90° turn @ 3-4g **Mark:** ___________

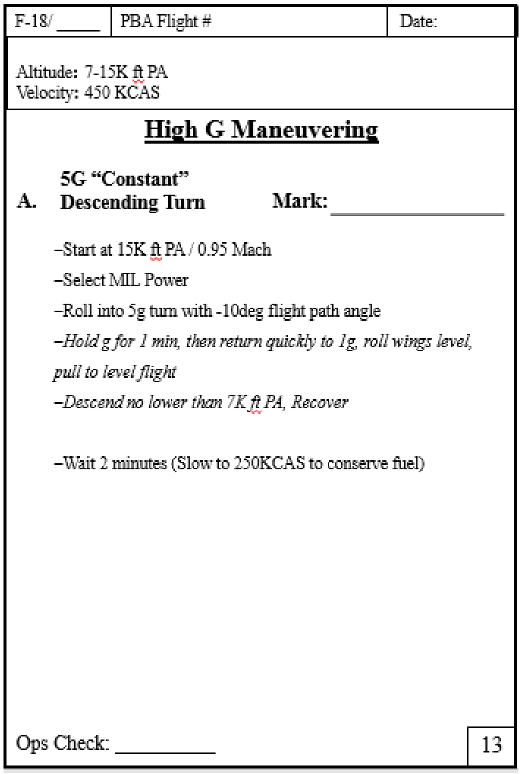
-400 KCAS
-Level at 12K ft PA
-Constant Power –MIL
-Airspeed will bleed

A2. 90° turn @ 4-5g **Mark:** ___________

-450 KCAS
-Level at 12K ft PA
-Constant Power –MIL
-Airspeed will bleed

Ops Check: __________

12



F-18/ _____ | PBA Flight # | Date:

Altitude: 7-15K ft PA
Velocity: 450 KCAS

High G Maneuvering

A. 5G "Constant" Descending Turn **Mark:** _________________

–Start at 15K ft PA / 0.95 Mach

–Select MIL Power

–Roll into 5g turn with -10deg flight path angle

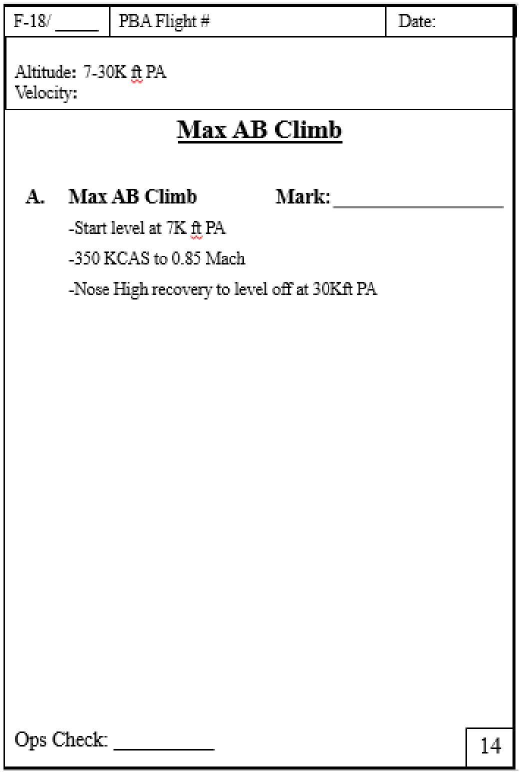
–Hold g for 1 min, then return quickly to 1g, roll wings level, pull to level flight

–Descend no lower than 7K ft PA, Recover

–Wait 2 minutes (Slow to 250KCAS to conserve fuel)

Ops Check: __________

13



F-18/ _____ | PBA Flight # | Date:

Altitude: 7-30K ft PA
Velocity:

Max AB Climb

A. Max AB Climb **Mark:** _________________

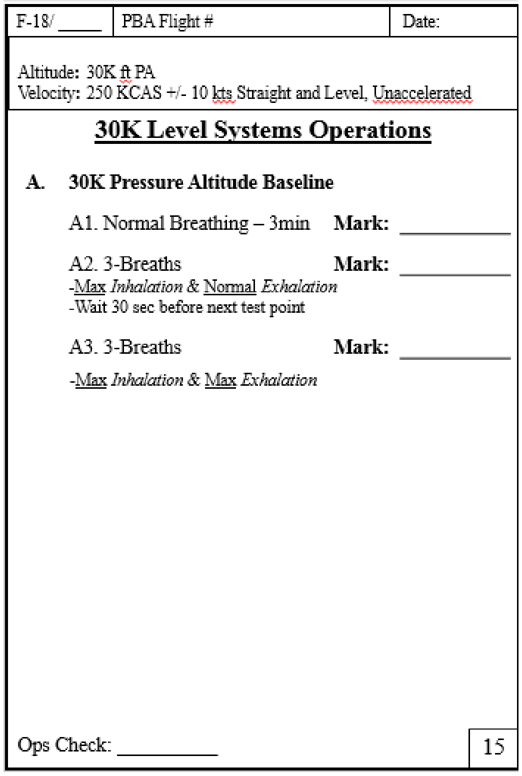
-Start level at 7K ft PA

-350 KCAS to 0.85 Mach

-Nose High recovery to level off at 30Kft PA

Ops Check: __________

14



F-18/ _____ | PBA Flight # | Date:

Altitude: 30K ft PA
Velocity: 250 KCAS +/- 10 kts Straight and Level, Unaccelerated

30K Level Systems Operations

A. 30K Pressure Altitude Baseline

A1. Normal Breathing – 3min **Mark:** ___________

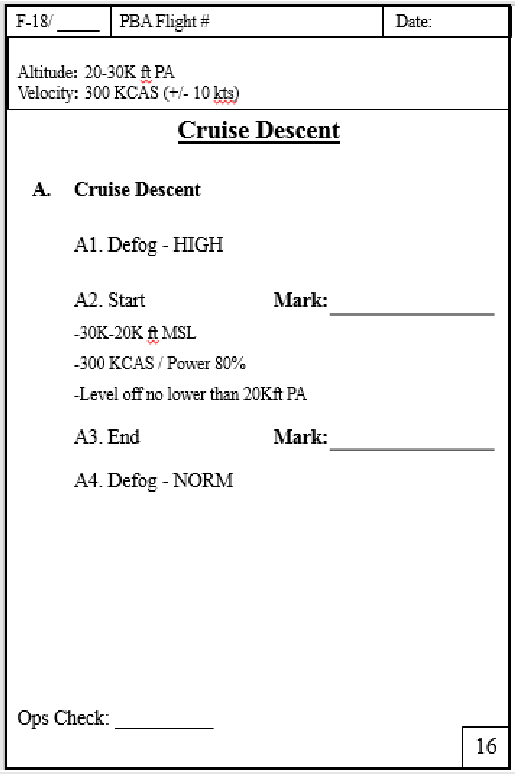
A2. 3-Breaths **Mark:** ___________
-Max *Inhalation* & Normal *Exhalation*
-Wait 30 sec before next test point

A3. 3-Breaths **Mark:** ___________

-Max *Inhalation* & Max *Exhalation*

Ops Check: __________

15



F-18/ ____	PBA Flight #	Date:

Altitude: 20-30K ft PA
Velocity: 300 KCAS (+/- 10 kts)

Cruise Descent

A. Cruise Descent

A1. Defog - HIGH

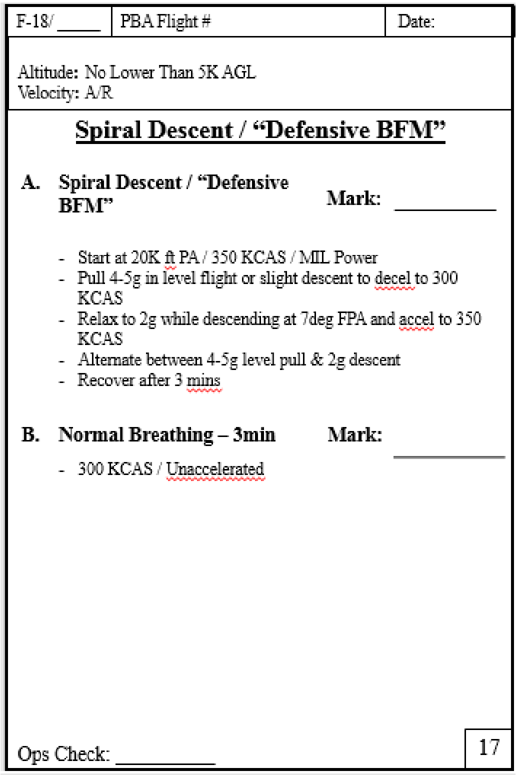
A2. Start **Mark:** ____________
-30K-20K ft MSL
-300 KCAS / Power 80%
-Level off no lower than 20Kft PA

A3. End **Mark:** ____________

A4. Defog - NORM

Ops Check: __________

16



F-18/ ____	PBA Flight #	Date:

Altitude: No Lower Than 5K AGL
Velocity: A/R

Spiral Descent / "Defensive BFM"

A. Spiral Descent / "Defensive BFM" **Mark:** __________

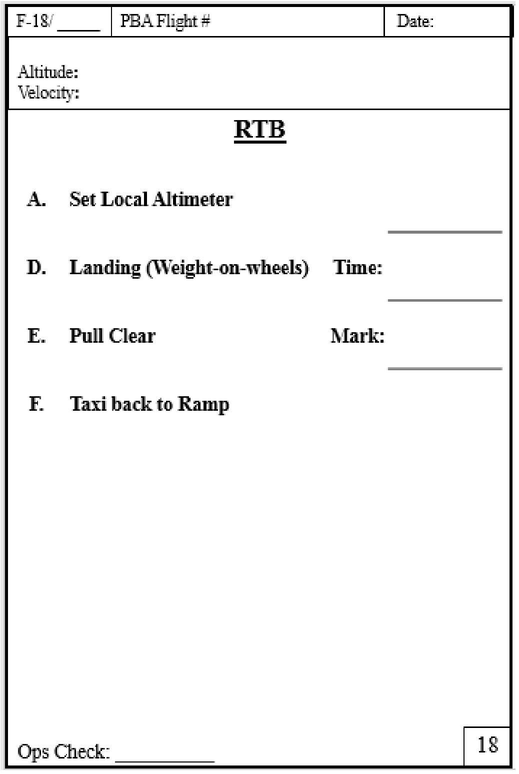
- Start at 20K ft PA / 350 KCAS / MIL Power
- Pull 4-5g in level flight or slight descent to decel to 300 KCAS
- Relax to 2g while descending at 7deg FPA and accel to 350 KCAS
- Alternate between 4-5g level pull & 2g descent
- Recover after 3 mins

B. Normal Breathing – 3min **Mark:** __________

- 300 KCAS / Unaccelerated

Ops Check: __________

17



F-18/ ____	PBA Flight #	Date:

Altitude:
Velocity:

RTB

A. Set Local Altimeter __________

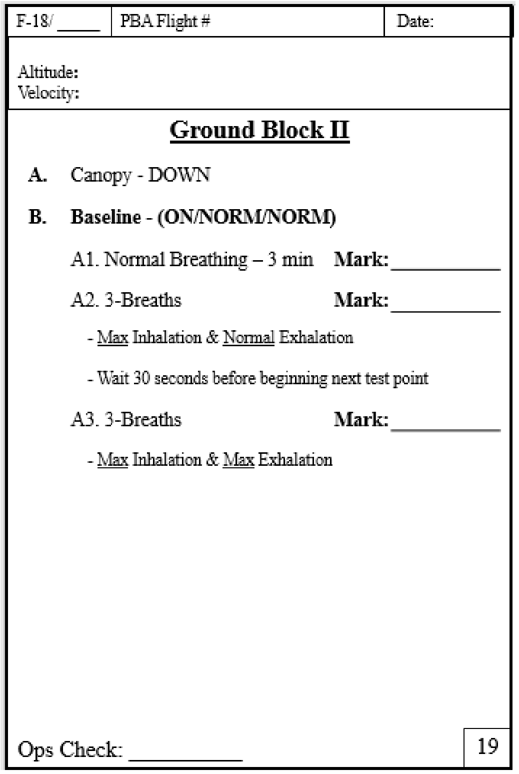
D. Landing (Weight-on-wheels) **Time:** __________

E. Pull Clear **Mark:** __________

F. Taxi back to Ramp

Ops Check: __________

18



F-18/ ____	PBA Flight #	Date:

Altitude:
Velocity:

Ground Block II

A. Canopy - DOWN

B. Baseline - (ON/NORM/NORM)

A1. Normal Breathing – 3 min **Mark:** __________

A2. 3-Breaths **Mark:** __________
- Max Inhalation & Normal Exhalation
- Wait 30 seconds before beginning next test point

A3. 3-Breaths **Mark:** __________
- Max Inhalation & Max Exhalation

Ops Check: __________

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Appendix 2: Fundamentals of Pilot Breathing

- This appendix contains links to the two animations discussed in PBA Volume I, Technical Section 2
    - Normal breathing animation
    - G-Breathing animation

Also the following:

The Fundamentals of How Regulators Operate in Breathing Systems

This appendix offers some fundamental descriptions of how regulators operate as a part of an integrated pilot breathing system. This appendix has three sections:

Section 1: Twenty statements about regulators in breathing systems
Section 2: Twenty paragraphs – expanding these statements with further explanation
Section 3: One scenario that considers a pilot breathing system upset, and the available information about that upset event

Section 1: Twenty statements about regulators in breathing systems:

1. Regulators act as pneumatic signal amplifiers. Regulators receive a relatively small pressure/flow pneumatic force input from pilot inhalation and deliver a larger pressure/flow response in the form of suppled air delivered to the mask.

2. Inhalation, which initiates and continuously controls regulator function, is highly variable. A pilot’s peak inhalation for any given breath can range from <1 mmHg to >30 mmHg. Rates of change of an individual’s inhalation pressure can range from <2 mmHg/sec to >200 mmHg/sec. The volume of a single breath can range from <0.5l to >5.0l.

3. Regulators need to provide air whether the call for air is gentle or intense, slow or sudden, small or large.

4. Breathing systems are compliant – some of the pressure/flow energy from inhalation is directed towards flexing breathing hoses and other compliant elements of the breathing system.

5. If the compliance of mechanical components like breathing hoses varies, regulator response varies. Compliance can vary if mask fit changes, or if hose length or hose shape changes. A regulator will deliver more air more quickly when it is installed in a breathing system with a short, stiff hose. A regulator will deliver less air with a greater delay when a longer hose or a softer hose is used.

6. Supply pressure effects regulator performance. Low pressure supply can delay delivery and limit driving force through restrictions in the flow path. High pressure supply can trigger overshoot and flow control instabilities. It is harder to smoothly match the timing and sequence of breathing when there is more energy to manage. Variable supply pressure is especially disruptive.

7. Regulators need to compensate for changes in cabin pressure and turbulence issues associated with airflow patterns in the cabin. This is accomplished through a system of diaphragms and through-holes. The through-holes have a specific size and are designed

for a specific pressure and a specific pressure differential. If the holes are too small, the response is too slow. If the holes are too large, internal pressure is not maintained and the regulator “droops” and the gas delivery is delayed.

8. Regulators need to compensate for changes in gas density. At high altitudes where gas density is lower, it takes a smaller pressure to deliver a set volume of breathing air. It is easier to breathe through a regulator at high altitudes, but the pilot receives fewer moles of breathing gas. An oxygen (O_2) schedule adjusts O_2 concentration to account for altitude/density effects.
9. Some regulators play an active and intentional role in controlling the O_2 percentage in pilot breathing air – some regulators play in unintentional role in controlling the O_2 percentage in pilot breathing air.
10. Breathing is dynamic. During inhalation, the absolute pressure, the delta pressure, the rate of pressure change, the corresponding flow, and the rate of change of flow are always changing. The hard thing about regulators is they need to do more than just deliver flow – they need to deliver the right amount of flow at the right time. Regulators need to match the sequence of pilot breathing.
11. A standard flow bench test of a regulator does not measure regulator dynamic response, nor does it measure the ability to match breathing sequence (which is the hard part of the regulator job). A standard flow bench test of a regulator involves fixed flows and constant conditions.
12. The most sophisticated standard test of a regulator involves a breathing simulator with a sinusoidal waveform. A sinusoidal waveform represents the smoothest rate of change possible. Sinusoidal waveform tests are non-conservative tests of breathing system dynamic response.
13. Pilots report difficulties breathing during and immediately after speaking, because the demand for air immediately after speaking is sudden and has a different sequence than the regulators are tuned for.
14. The hardest job of a regulator is matching breathing sequence; the regulator must match the timing of inhalation initiation, velocity increases, and velocity decreases.
15. The hardest conditions for matching breathing sequence involve:
    - variable supply pressure
    - variable cabin pressure
    - large and variable amounts of system compliance
    - talking and other sudden and variable demands for air
    - long breathing hoses
    - mask valves that are sticky or unseated
16. There is no Military Standard (MIL-STD) test that measures the ability of a regulator in a pilot breathing system to match breathing sequence. There is no MIL-STD requirement related to breathing sequence.
17. Breathing hysteresis and breathing phase shift are standard and quantitative measurements of system breathing sequence match (or breathing sequence insults).

Recommended requirements for breathing system performance are less than 0.7 lps for breathing hysteresis and less than 30 degrees for breathing phase shift.

18. Regulators can insult breathing sequence both ways; sometimes they deliver not enough air early in the inhalation, and too much air late in the inhalation – sometimes they deliver too much air early in inhalation, and not enough air late in inhalation.
19. Regulators sometimes suffer a flow control problem where they deliver a small amount of flow at a high velocity.
20. Regulators sometimes suffer a flow control problem where they interrupt speaking, by delivering a sudden surge of air while the pilot is trying to speak and is exhaling.

Section 2: Twenty paragraphs about regulators in breathing systems:

1. *Regulators act as pneumatic signal amplifiers. Regulators receive a relatively small pressure/flow pneumatic force input from pilot inhalation and deliver a larger pressure/flow response in the form of suppled air delivered to the mask.* Regulators receive a small pressure signal – that pressure signal is limited by the pressure force and volume of pilot breathing. This pressure fluctuation triggers regulator function – it serves as the control signal for the regulator. The job of a regulator is to receive air at high pressure and deliver the appropriate amount to the pilot at the correct time. The magnitude of the pressure forces involved in delivering air are substantially greater than the magnitude of the pressure forces involved in pilot demand. Some people find it helpful to think of a regulator as a pneumatic amplifier – especially when comparing different types of regulators. Some regulators quickly convert a small amount of signal into a large and sudden pneumatic delivery – these regulators can be thought to have “high gain.” These “high gain” regulators may have fewer flow delays, but they are less stable and more prone to overshoot.
2. *Inhalation, which initiates and continuously controls regulator function, is highly variable. A pilot’s peak inhalation for any given breath can range from <1 mmHg to >30 mmHg. Rates of change of an individual’s inhalation pressure can range from <2 mmHg/sec to >200 mmHg/sec. The volume of a single breath can range from <0.5l to >5.0l.* Regulators receive a pressure signal from pilot breathing that controls function– that pressure signal will vary dramatically, because breathing is highly variable. Normal resting breathing in open air generally involves pressure changes on the order of 1 to 3 mmHg. The greatest amount of pressure lungs can apply (under static, no-flow conditions) can be >30 mmHg. Rates of pressure increase and decrease can change by a factor of 100. The volume of a single breath can change by a factor of 10. Regulators receive pressure signals that are highly variable in magnitude, duration, and rate of change.
3. *Regulators need to provide air whether the call for air is gentle or intense, slow or sudden, small or large.* Pneumatic signal amplification would be comparatively easy if the pilot’s breathing demand were consistent. A regulator could be tuned to match a specific breathing profile – but tuning to match the needs of deep regular breaths would fail if the pilot was requesting slow gentle breathing, with a low flow and a small rate of change.

4. *Breathing systems are compliant – some of the pressure/flow energy from inhalation is directed towards flexing breathing hoses and other compliant elements of the breathing system.* The job of a regulator would be substantially easier if the pilot breathing system was rigid and perfectly sealed. If the pilot breathing system was sealed and rigid, there would be a larger pressure signal caused by inhalation and the inhalation pressure signal would be more repeatable. Actual pilot breathing systems are compliant – hoses flex, and gas leaks around the face seal of the mask. When a pilot takes an inhale breath, some of the inhalation pressure energy goes to drop the pressure of the line – but some of the inhalation pressure energy goes to flexing the breathing hose and causing in-leakage around the mask. When compliance changes from flight to flight, regulator response will change from flight to flight – even if the mechanical elements of the regulator are performing identically.
5. *If the compliance of mechanical components like breathing hoses varies, regulator response varies. Compliance can vary if mask fit changes, or if hose length or hose shape changes. A regulator will deliver more air more quickly when it is installed in a breathing system with a short, stiff hose. A regulator will deliver less air with a greater delay when a longer hose or a softer hose is used.* Two-seat planes, where the length of the hose for the front seat and the length of hose for the back seat are different will have different breathing responses – even if the mechanical elements of the regulator are performing identically. Generally, the pilot with the longer hose will have the more difficult time breathing, because the volume of gas is greater, the pressure signal will be smaller, the amount of possible compliance is larger and more variable, and it takes longer for the air to reach the pilot.
6. *Supply pressure effects regulator performance. Low pressure supply can delay delivery and limit driving force through restrictions in the flow path. High pressure supply can trigger overshoot and flow control instabilities. It is harder to smoothly match the timing and sequence of breathing when there is more energy to manage. Variable supply pressure is especially disruptive.* MIL-STD tests focus on the ability for a regulator to flow freely and deliver a sufficient supply of air to the pilot – even when the supply pressure is low. This is important, but it is not sufficient. Regulators must deliver a consistent amount of flow for a given demand – regardless of supply pressure. It is hard to deliver a consistent amount of flow – with consistent timing and sequence – if supply pressure varies dramatically. Pneumatic flow control systems are prone to overshoot with high supply pressure and suffer delays at low supply pressure.
7. *Regulators need to compensate for changes in cabin pressure and turbulence issues associated with airflow patterns in the cabin. This is accomplished through a system of diaphragms and thru-holes. The thru-holes have a specific size and are designed for a specific pressure and a specific pressure differential. If the holes are too small, the response is too slow. If the holes are too large, internal pressure is not maintained and the regulator "droops" and the gas delivery is delayed.* Regulators are designed to leak slightly, with internal high-pressure gas leaking through the regulator to the outside. This slight leakage ensures reliable performance in a cabin environment with increasing pressure (descent) or decreasing pressure (ascent). This intentional leakage must be manufactured to meet a specific set of conditions – with a set supply pressure, a set cabin pressure, and a set rate of cabin pressure change. Different conditions result in different

performance. Systems designed to respond to faster rates of change of cabin pressure are generally less capable to meet demands for fast increases in inhalation. Systems designed for fast response to changes in inhalation are generally less capable to correct for sudden changes in cabin pressure.

8. *Regulators need to compensate for changes in gas density. At high altitudes where gas density is lower, it takes a smaller pressure to deliver a set volume of breathing air. It is easier to breathe through a regulator at high altitudes, but the pilot receives fewer moles of breathing gas. An O_2 schedule adjusts O_2 concentration to account for altitude/density effects.* At high altitudes, cabin pressure is low, the pressure in the breathing gas line is low, and small changes in pressure can maintain high volumetric flow rates. Regulator function is easier at high altitudes – small changes in pressure can meet flow requirements – but the reduced density of gas means that a given volume of air contains fewer moles of O_2. An altitude/ O_2 percentage schedule accounts for this and requires that pilot breathing gas contains a higher percentage of O_2 at higher altitudes.
9. *Some regulators play an active and intentional role in controlling the O_2 percentage in pilot breathing air; some regulators play an unintentional role in controlling the O_2 percentage in pilot breathing air.* Demand regulators receive 100% of pilot breathing gas from a high-pressure supply. If there is an altitude/O_2 percentage schedule, the gas supply system has to adjust the concentration of O_2. One example is an On-Board Oxygen Generating System (OBOGS) that operates with a different cycle time at high altitudes to provide greater O_2 percentage. The demand regulator does not intentionally mix gases and adjust O_2 concentration. Diluter-demand regulators mix high-pressure supply gas with cabin air. Diluter-demand regulators intentionally adjust O_2 concentration. For a given altitude – the ratio of high-pressure gas to cabin gas should be fixed regardless of breathing profile. In practice, this this ratio is not fixed. When a pilot takes a quick deep breath, flow rate from the high-pressure gas is choked and more cabin air is introduced. The pilot taking a quick deep breath from a diluter-demand regulator generally gets a full breath, and it is generally easy to breathe, but the O_2 concentration may be lower than specified. The pilot taking a quick deep breath from a demand regulator can suffer a choke in the breathing gas supply. The O_2 concentration will match the schedule, but the air will come late, it will be difficult to breathe, and the quantity of gas may be reduced.
10. *Breathing is dynamic. During inhalation, the absolute pressure, the delta pressure, the rate of pressure change, the corresponding flow, and the rate of change of flow are always changing. The hard thing about regulators is they need to do more than just deliver flow – they need to deliver the right amount of flow at the right time. Regulators need to match the sequence of pilot breathing.* Inhalation is not simple. The amount of air requested at any given instant changes, and the rate of change is variable. Delivering air to the pilot early disrupts breathing. Delivering air to the pilot late disrupts breathing. In the early stages of inhalation, increasing the delivery rate too quickly disrupts breathing. In the early stages of inhalation, increasing the delivery rate too slowly disrupts breathing. In the late stages of inhalation, decreasing the delivery rate too quickly disrupts breathing. In the late stages of inhalation, decreasing the delivery rate too slowly disrupts breathing.
11. *A standard flow bench test of a regulator does not measure regulator dynamic response, nor does it measure the ability to match breathing sequence (which is the hard part of the*

regulator job). A standard flow bench test of a regulator involves fixed flows and constant conditions. A standard flow bench sets and fixes supply pressure. A standard flow bench sets and fixes cabin pressure (usually at lab ambient pressure). A standard flow bench sets and fixes demand pressure – and measures the corresponding flow for these fixed pressure conditions. A standard flow bench measures steady state flow. A regulator in a standard flow bench has internal components that are generally not moving. The difficult job of a regulator is matching breathing sequence and making dynamic changes that match the dynamic changes of pilot breathing. A standard flow bench test does not test the difficult part of regulator performance.

12. *The most sophisticated standard test of a regulator involves a breathing simulator with a sinusoidal waveform. A sinusoidal waveform represents the smoothest rate of change possible. Sinusoidal waveform tests are non-conservative tests of breathing system dynamic response.* Testing a regulator with a breathing simulator is a dynamic test of regulator function. Breathing simulator tests are tests of the difficult part of regulator performance. Pilot reports of difficulty breathing indicate that difficulties are most likely when changes in the breathing sequence are the most abrupt; such as taking a fast breath at the end of talking, or taking a large and sudden breath during an anti-g straining maneuver. The standard breathing simulator uses a sinusoidal waveform. The sinusoidal waveform is the smoothest and most uniform dynamic pattern possible. Sinusoidal breathing simulators are the most non-conservative dynamic tests possible.

13. *Pilots report difficulties breathing during and immediately after speaking, because the demand for air immediately after speaking is sudden, and has a different sequence than the regulators are tuned for.* Meeting a sudden change in breathing sequence is the hardest thing for a regulator to do. Sudden changes cause changes in system compliance. Sudden changes cause fast dynamic changes in the regulator.

14. *The hardest job of a regulator is matching breathing sequence; the regulator must match the timing of inhalation initiation, velocity increases, and velocity decreases.* There is an inherent lag in a regulated pilot breathing system: first the pilot needs to initiate the inhalation, then the pressure of the mask/line control volume needs to drop, then the regulator needs to receive the signal, then the regulator needs to mechanically actuate and respond to the signal, then the gas needs to flow through the regulator and through the mask/line control volume. Matching the timing and matching the sequence and increasing flow rate when the pilot desires increasing flow rate and decreasing the flow rate when the pilot desires decreased flow rate – the dynamic response is the hard thing.

15. *The hardest conditions for matching breathing sequence involve:*
    - *variable supply pressure*
    - *variable cabin pressure*
    - *large and variable amounts of system compliance*
    - *talking and other sudden and variable demands for air*
    - *long breathing hoses*
    - *mask valves that are sticky or unseated*

    Meeting the dynamic response and matching the timing of the pilot’s breathing sequence is always the hard part of the job. Sometimes, aspects of the pilot breathing system can make this especially hard. It is harder to match the timing of the breathing sequence when the supply pressure is changing, because response rates of the internal components in the regulator change when supply pressure changes. Cabin pressure changes complicate system response. Compliance in the breathing system causes delays. Changes in compliance results in inconsistent timing. Sudden demands for air limit the allowable time for system response. Long breathing hoses delay the pressure signal and delay the delivery of gas. Mask components, especially inhalation and exhalation valves, can delay system response if they are sticky.

16. *There is no MIL-STD test that measures the ability of a regulator in a pilot breathing system to match breathing sequence. There is no MIL-STD requirement related to breathing sequence.* Timing, and matching the breathing sequence is the difficult and important job – but there is no standard way to test timing and breathing sequence, and there are no specifications related to timing and breathing sequence.
17. *Breathing hysteresis and breathing phase shift are standard and quantitative measurements of system breathing sequence match (or breathing sequence insults). Recommended requirements for breathing system performance are less than 0.7 lps for breathing hysteresis and less than 30 degrees for breathing phase shift.* Quantitative measures of the ability of a breathing system to match the timing and breathing sequence of a pilot have been developed. Breathing hysteresis and breathing phase shift quantitatively and systematically measure timing and sequence – this is not a subjective assessment. Breathing hysteresis and breathing phase shift have been evaluated as part of the Pilot Breathing Assessment – there is a sufficient database to set provisional standards.
18. *Regulators can insult breathing sequence both ways; sometimes they deliver not enough air early in the inhalation, and too much air late in the inhalation – sometimes they deliver too much air early in inhalation, and not enough air late in inhalation.* Measurements of breathing hysteresis and breathing phase shift show that regulators in breathing systems can err in both directions, sometimes supplying too early and sometimes too late. System lag is expected, delivering too early is likely caused by system interactions where the end of the previous breath effects system performance for the following breath.
19. *Regulators sometimes suffer a flow control problem where they deliver a small amount of flow at a high velocity.* Regulators are constantly adjusting to find a solution to the breathing supply problem. Sometimes, the regulators shift between overshoot condition and overshoot condition – resulting in a system that provides a small amount of high velocity gas.
20. *Regulators sometimes suffer a flow control problem where they interrupt speaking, by delivering a sudden surge of air while the pilot is trying to speak and is exhaling.* Pilots report getting their speech cut off by a regulator that pushes a large amount of air down their throat – making speech impossible. This occurs because a pilot will take a quick inhale breath at the end of a sentence – this quick breath triggers a large surge of gas from the regulator – which makes speaking impossible.

Section 3: Summary Scenario:

When considering the difficult job of matching breathing system supply sequence to breathing system demand sequence, the following scenario makes sense:

- Pilot senses problems flying, declares a PE
- Medical assessment indicates signs of hypoxia or "hypoxia-like" symptoms
- Regulator is removed from the pilot breathing system, and tested as a single component
- Regulator is tested under fixed flow conditions
- Breathing hysteresis / breathing phase shift are not measured
- No anomalies are detected
- Event is declared a UPE

The pilot suffered a PE because the pilot breathing system inflicted breathing sequence insults on the pilot, which compromised breathing, choked the supply air to the pilot, and triggered hypoxia. The cause could have been a stuck exhalation valve, a breathing hose that was too long for the system tuning, cabin pressure surges, supply pressure variability, or a breathing demand profile that was outside the tuning range for the regulator. These problems will never be identified by a post event bench test of the regulator as an isolated component (under fixed flow conditions). These problems can be identified by measuring pilot breathing in the jet, and measuring breathing hysteresis and breathing phase shift.

PilotBreathingNORM_anim.mp4

PilotBreathingGstrain_anim.mp4

Appendix 3: VigilOX Sensors

Department of Defense (DoD) Technology Readiness Levels (TRL)

The Department of Defense (DoD) Technology Readiness Levels (TRLs) are defined in the table below:

Level	Definition	DoD DAG Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology’s basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development are initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively “low fidelity” compared to the eventual system. Examples include integration of “ad hoc” hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Inhalation and Exhalation Sensor Block Evolution

Source Material:	PowerPoint
Title:	VigilOx™ Evolution
Date:	12/04/2018
Presenter:	Lucas Mesmer, Cobham Senior Design Engineer
File Name:	2018_11_30_VigilOx_Evolution.ppt

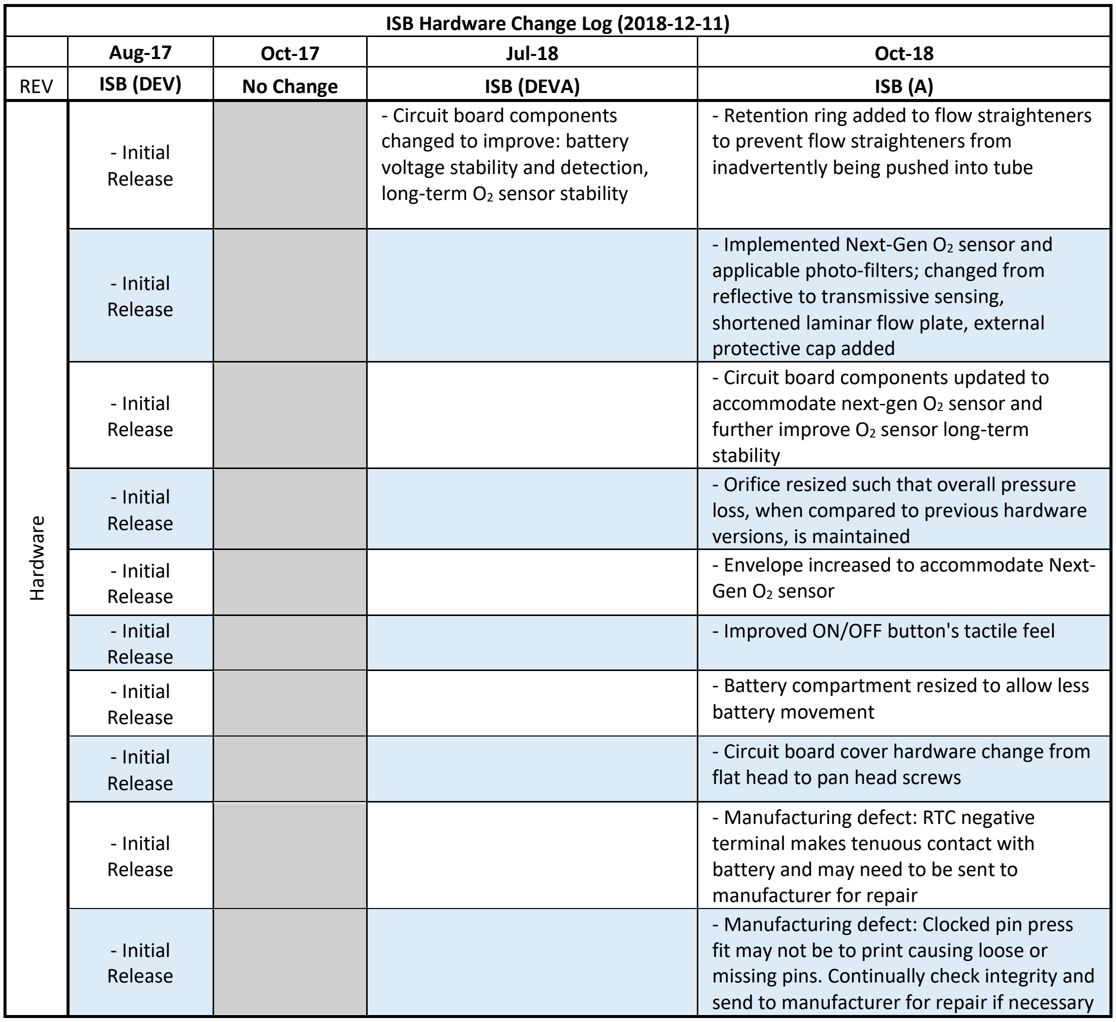
There are two components of the VigilOx. There is the Inhalation Sensor Block (ISB) and the Exhalation Sensor Block (ESB). These two systems collect data independently. Within each system there are physical components (hardware) and digital components (software). The information below provides the version numbers and known modifications for the hardware and software of the ISB and ESB across the various builds between the initial release of the ISB in August 2017, ESB in October 2017 to December 2018.

Date	Name	Block	Software Version	Software Changes	Hardware Version	Hardware Changes
Aug 2017	Initial Release	ISB	V0.24	Initial Release (United States Air Force School of Aerospace Medicine (USAFSAM))	DEV	Initial Release (USAFSAM)
Oct 2017	Update	ISB	V0.26	• Revised Oxygen (O_2) sensor implementation to utilize Nano-Fiber • Added O_2 humidity compensation capability	DEV	• O_2 sensing material changed from Ruthenium to Nano-Fiber
	Initial Release	ESB	V0.12	Initial Release (USAFSAM)	DEV	Initial Release (USAFSAM)
Jul 2018	Cardinal Update	ISB	V0.34	• Data Filtering - Improved data filtering and detection of “bit-collisions” • O_2 Sensor - Limited maximum reported partial pressure to current absolute gas pressure • Humidity Sensor - Revised sensor heater control, Bounded by 0 and 100% • Cabin Pressure Sensor - Implemented temperature compensation • Real-Time Clock - Improved long-term stability (when used in conjunction with AMPSS TOOL Rev D or later) • Micro-SD Card - Improved robustness of usability checks • Status LED - New warning/message scheme • Password Protocol - Added password protection on certain software constants and calibration tables	DEVA	• Circuit Board - Replaced various components to improve sensor bus voltage stability and long-term O_2 sensor stability
		ESB	V0.27	• CO_2 Sensor - Tare function available for calibration and improved heater control • Flow Sensor - Limited maximum flow to 400 slpm	(-)	• Mask Pressure Adapter and Tube Retainers • Exhalation Tube Adapter Ring • Battery Divider - Chamfer increased to ease installation and removal of batteries • ON/OFF Button

Date	Name	Block	Software Version	Software Changes	Hardware Version	Hardware Changes
						• Humidity and Gas Temperature Sensor Board - Porous sock installed
Oct 2018	Secondary Update	ISB	V1.01	• O_2 Sensor - Calibration tables and partial pressure of O_2 calculation updated to accommodate new O_2 sensing material	A	• Envelope - Increased slightly to accommodate O_2 sensor and hardware changes • Circuit Board - Updated components and layout to accommodate new O_2 sensor and provide further improvements to long-term O_2 sensor stability • O_2 Sensor Redesign: ○ Transmissive (same as ESB) ○ Next-Gen Sensing Material ▪ Humidity insensitive: ▪ Altitude insensitive – no change ▪ Temperature sensitive – no change ▪ Little to no photo-bleaching or aging ▪ Response time similar to previous sensors ▪ Increased resolution at low O_2 concentrations (<190 mmHg Partial Pressure of Oxygen (ppO_2)) ▪ Decreased resolution at high O_2 concentrations (>190 mmHg ppO2) ▪ Recommended usage time between calibrations not yet determined • Flow Straightener Retention • Power Button - Button and cover redesigned to improve tactile feel • Battery Compartment - Resized to better fit battery
		ESB	V1.01	• Mask Pressure Sensor - Will tare simultaneously with flow sensor • Bootloader - Minimizes occurrence of solid red light on startup	A	None

VigilOX Change Logs and Known Issue Revisions from Cobham

Source Material:	Excel Sheet
Title:	VigilOx Evolution
Date:	12/11/2018
Presenter:	Lucas Mesmer and Zoe Rabinowitz, Cobham Engineering
File Name:	2019_04_22_VigilOx_Evolution.xlsx



ISB Hardware Change Log (2018-12-11)

	Aug-17	**Oct-17**	**Jul-18**	**Oct-18**
REV	**ISB (DEV)**	**No Change**	**ISB (DEVA)**	**ISB (A)**
Hardware	- Initial Release		- Circuit board components changed to improve: battery voltage stability and detection, long-term O_2 sensor stability	- Retention ring added to flow straighteners to prevent flow straighteners from inadvertently being pushed into tube
	- Initial Release			- Implemented Next-Gen O_2 sensor and applicable photo-filters; changed from reflective to transmissive sensing, shortened laminar flow plate, external protective cap added
	- Initial Release			- Circuit board components updated to accommodate next-gen O_2 sensor and further improve O_2 sensor long-term stability
	- Initial Release			- Orifice resized such that overall pressure loss, when compared to previous hardware versions, is maintained
	- Initial Release			- Envelope increased to accommodate Next-Gen O_2 sensor
	- Initial Release			- Improved ON/OFF button's tactile feel
	- Initial Release			- Battery compartment resized to allow less battery movement
	- Initial Release			- Circuit board cover hardware change from flat head to pan head screws
	- Initial Release			- Manufacturing defect: RTC negative terminal makes tenuous contact with battery and may need to be sent to manufacturer for repair
	- Initial Release			- Manufacturing defect: Clocked pin press fit may not be to print causing loose or missing pins. Continually check integrity and send to manufacturer for repair if necessary

ESB Hardware Change Log (2018-12-11)					
	Aug-17	**Oct-17**		**Jul-18**	**Oct-18**
REV		**ESB (DEV)**	**ESB (DEVA)**	**ESB (-)**	**ESB (A)**
Hardware		- Initial Release	- Circuit board components changed to improve: -battery voltage stability and detection - long-term O_2 sensor stability	- Mask pressure adapter reconfigured to remove pig-tail; female and male connections were reversed - Adapter body changed from polygonal to rectangular profile	- Implemented Next-Gen O_2 sensor and applicable photo-filters
		- Initial Release		- Mask pressure tube retainers changed from elastic rings to molded retainers to securely grip tube	- Circuit board components updated to accommodate next-gen O_2 sensor and further improve O_2 sensor long-term stability
		- Initial Release		- Exhalation tube adapter ring retention set-screws reconfigured to prevent damage to exhalation valve threads - Set screws replaced with button-head screws	- Envelope increased to accommodate next-gen O_2 sensor
		- Initial Release		- Battery divider chamfer increased to ease installation and removal of batteries	
		- Initial Release		- Improved ON/OFF button's tactile feel	
		- Initial Release		- Porous sock installed over humidity and gas temperature sensor board to repel water droplets	
		- Initial Release			- Manufacturing defect: RTC negative terminal makes tenuous contact with battery and may need to be sent to manufacturer for repair

ISB Software Change Log (2018-12-11)					
		Aug-17	**Oct-17**	**Jul-18**	**Oct-18**
Version Number		**ISB V0.24**	**ISB V0.26**	**ISB V0.34**	**ISB V1.01**
Sensor	**Real Time Clock**	- Initial Release		- AMPSS TOOL Version D and later allows for minor adjustments of clock to bound drift by ~+/- 2.6 seconds per 24 hours	
	Flow	- Initial Release			
	Gas (Line) Pressure	- Initial Release			
	Gas (Line) Temperature	- Initial Release			
	Humidity	- Initial Release		- Revised humidity sensor heater control to prevent heater overshoot - Bounded sensor by 0 and 100% RH	
	O_2	- Initial Release	- Revised O_2 sensor implementation to utilize Nano-Fiber - Added O_2 humidity compensation capability	- Limited maximum reported partial pressure to current absolute gas pressure measurement	- Calibration tables and partial pressure of O_2 calculation updated to accommodate Next-Gen O_2 sensing material
	Cabin Pressure	- Initial Release		- Implemented temperature compensation	
	Cabin Temperature	- Initial Release			
	Acceleration	- Initial Release			
	Data Filtering	- Initial Release		- Improved data filtering to detect and eliminate "bit-collisions" - Filter settings are configurable for each sensor	
	Status LED	- Initial Release		- Implemented new warning/message scheme	
	Miscellaneous	- Initial Release		- Improved robustness of Micro-SD Card usability checks - Implemented password protocol to protect certain software constants and calibration tables	

ESB Software Change Log (2018-12-11)					
			Oct-17	**Jul-18**	**Oct-18**
Version Number			**ESB V0.12**	**ESB V0.26, V0.27, V0.28**	**ESB V1.01**
Sensor	**Real Time Clock**		- Initial Release	- AMPSS TOOL Version D and later allows for minor adjustments of clock to bound drift by ~+/- 2.6 seconds per 24 hours	
	Flow		- Initial Release	- V0.26 and later: limits maximum reported flow to 400 slpm - V0.27 and later: References correct high pressure sensor for flow measurements above ~200 slpm	
	Gas (Line) Pressure		- Initial Release		
	Gas (Line) Temperature		- Initial Release		
	Humidity		- Initial Release	- Revised humidity sensor heater control to prevent heater overshoot - Bounded sensor by 0 and 100% RH	
	O_2		- Initial Release	- Limited maximum reported partial pressure to current absolute gas pressure measurement	- Calibration tables and partial pressure of O_2 calculation updated to accommodate Next-Gen O_2 sensing material
	Cabin Pressure		- Initial Release	- Implemented temperature compensation	
	Cabin Temperature		- Initial Release		
	Acceleration		- Initial Release		
	Carbon Dioxide		- Initial Release	- Factory tare function available for calibration - Heater control adjusted to minimize overshoot of temperature control	
	Mask Pressure		- Initial Release	- V0.28 and later: tares simultaneously with flow sensor	
	Data Filtering		- Initial Release	- Improved data filtering to detect and eliminate "bit-collisions" - Filter settings are configurable for each sensor	
	Status LED		- Initial Release	- Implemented new warning/message scheme	
	Miscellaneous		- Initial Release	- Improved robustness of Micro-SD Card usability checks - Implemented password protocol to protect certain software constants and calibration tables	- Bootloader updated to minimize occurrence of solid red light on startup

Appendix 4: Pilot Physiology

Standards, Hyperoxia and Hypoxia

Standards have been developed steadily to provide adequate breathing gasses to combat the effects of altitude on the human aircrew members. World War II saw the rapid expansion of knowledge in the development of countermeasures and standards to prevent the medical consequences of altitude. At the outset of the war, aircraft were neither pressurized nor heated. The aircraft had to fly as high as possible to avoid ground fire. Flying at 25,000 to 30,000 ft, the crews suffered hypoxia from the lack of oxygen (O_2) and decompression sickness from the low pressure. Hypobaric chambers were developed to study the effects and develop these standards.

Today's high-performance aircraft are pressurized during flight in order to provide acceptable pressure and thermal environments. Hypoxia during flight in these aircraft is prevented by delivering appropriate concentrations and pressure of O_2 in relation to the cabin altitude. The delivery of 100% O_2 as a routine in the flight environment has advantages and disadvantages. The United States Air Force (USAF) uses breathing systems that provide a mixture of O_2 and air until 10,000 ft and then 100% O_2 is delivered. Hypoxia is a critical hazard that follows a failure of the life support systems to provide adequate O_2 relative to the altitude and dynamic flight environments of fighter aircraft. Modern 4th and 5th generation fighter aircraft fly higher than previous generations of aircraft. Above 40,000 to 43,000 ft, loss of cabin pressure requires the immediate provision of breathing gas with 100% O_2 and an appropriate pressure to supply the alveolar O_2 concentration to prevent the immediate onset of hypoxia. Numerous studies have investigated the relationship between the concentration of O_2 supplied in the inspired gas and the cabin altitude. Also, work has been done on prevention of hypoxia and pressure breathing employing partial-pressure suits with oro-nasal masks. The results were encompassed in the Air Standardization Coordination Committee (Air Standards 61/101/6A and 61/101.1C) and the NATO Military Agency for Standardization (STANANG 3863).

Fighter aircraft in service today and for the future utilize the maximum differential pressure of 5.0 Lb in^2 for aircraft altitudes above 23,000 ft. Numerous physiological factors influence the specifications of the gas composition for the aviator. Liquid O_2 systems utilize Nitrogen as the diluent gas as it is readily available for mixing prior to delivery to the pilot. Molecular sieve concentrators a breathable mixture that contains argon as well as O_2 and nitrogen. The maximum concentration of argon is 5 to 6%. Studies done by Cooke et al. showed that these lower concentrations of argon had no discernable physiological effect and it was safe as a diluent gas.

The standard concentration of O_2 at a minimum to avoid hypoxia should be equal to or greater than the partial pressure of oxygen (ppO_2) in the alveolar gas at sea level. This equates to 103 mmHg. Another factor to consider is to prevent impairment of the aircrew if a sudden loss of cabin pressure occurs at high altitude. If a rapid decompression above 30,000 ft occurs, the rapid development of hypoxia will ensue and incapacitate the pilot until such time as adequate O_2 to the alveolus is provided and the cells can recover function.

Breathing high concentrations of O_2 in the operational environment of highly maneuverable aircraft significant disadvantages. It produces acceleration induced atelectasis in addition to absorption atelectasis and delayed otic barotrauma. The Royal Air Force (RAF) in the 1950s used pressure demand non-dilutional regulators that delivered 100% O_2. Reports revealed that this produced symptoms of dry coughing accompanied by a sense of difficulty breathing. These occurred during and after flights, especially those exposed to $+G_z$ accelerations with G-trousers. Also notable were the episodes of substernal chest pain and tightness in the chest. (A similar set of symptoms occurred with the pressurized high concentrations of O_2 used from startup to post landing in the F-22.) The coughing was usually provoked by attempts to take deep breaths wither in flight or upon standing and exiting the cockpit post flight. The coughing and shortness of breath lasted from a couple minutes to episodes lasting 10 to 30 minutes. Several studies conducted after this showed that 80 = 85% of pilots had the symptoms with inhaled 100% O_2 and exposure to $+G_z$ loads above 3 to 4 G. Chest radiographs revealed marked collapse of the basal segments of the lungs. The atelectasis remained until the individual took deep breaths or coughed. The chest x-ray returned to normal usually within 10 to 30 minutes, but occasionally these findings remained for over 24 hours. Centrifuge studies confirmed that absorption atelectasis by breathing 100% O_2 combined with acceleration atelectasis with a $+G_z$ load greater than 3 to 4Gs is significantly worsened by the inflation of G-suits. This is due to the rapid absorption of gas in non-ventilated alveoli in the base of the lungs. The nitrogen is replaced with O_2 from breathing high concentrations of O_2. Nitrogen is not absorbed into the circulatory system as acts as a splint to prevent alveolar collapse. The $+G_z$ acceleration increases the weight of the upper lung segments resulting in the compression of the lower segments. This results in closing the small and intermediate airway passages. This is accentuated by the inflation of the abdominal bladder of the G suit.

If air is breathed prior to exposures to high G_z loading the nitrogen in the non-ventilated alveoli maintains the patency of the alveoli while under acceleration loads. Nitrogen has a far lower solubility in blood, and it acts as a break on the total absorption of gas from the alveoli. If the inspired gas is 100% O_2, this displaces the nitrogen in the alveoli. Since the remaining gas in the alveoli is principally O_2, the blood picks up this O_2 rapidly and thus causes the alveoli to collapse. The surface forces cause the alveoli to remain collapsed until they are reopened by deep inspiration or coughing. This is referred as absorption atelectasis. In animal studies, Rahn and Dale showed that the rate of absorption from non-ventilated alveoli is increased by 60% when 100% O_2 is inhaled rather than air. RAF and USAF flight and lab studies established clearly that significant acceleration atelectasis does not occur with inhaling > 40% nitrogen. Thus, the combination of absorption and acceleration atelectasis has an extremely significant impact in the high G aircraft environment. With the introduction of molecular sieve concentrators, there is an increase in the amount of argon produced in the inhaled gas mixtures. Haswell et al. studied the effect of argon in the gas mixtures and showed that it was just as effective as nitrogen alone in prevention of acceleration atelectasis. Ernsting et al. in animal studies showed that up to 25,000 ft, 40% nitrogen was required to prevent acceleration atelectasis. Flight studies also confirmed that 40% nitrogen was required to inhibit acceleration atelectasis up to a pressure-altitude of 20,000 ft. Since 1960, the RAF has required that O_2 concentration will not exceed 60% at cabin altitudes less than 20,000 ft. The specifications for the molecular sieve concentrator for the RAF Harrier GR Mk 5 aircraft specified the minimum nitrogen concentration as 40% or greater below 16,000 to 25,000 ft. The concentrator of the AV-8B derivative of the Harrier delivered 94% O_2 and this resulted in prominent acceleration atelectasis with moderate G_z loads.

Venous blood continues to flow through the atelectatic segments and produces a right to left shunt. A right to left shunt is usually a cardiac abnormality in which O_2-poor blood gets from the right half of the heart into the left side and thus into the systemic circulatory system. In this case it is the lung segment collapse that causes the O_2-poor blood to return to the heart simulating a heart defect. The consequence of this is dependent on the magnitude of the acceleration atelectasis. Moderate exposures of 4 G_z with 100% O_2 can result in a right-to left shunt of 20 to 25% unsaturated blood in the systemic output of the heart. (Green et al.). This would not have a significant effect with 100% O_2 at low altitudes but would produce a severe condition and significant hypoxia if the alveolar PO_2 fell below 103 mmHg. The above reasons were the driving force behind limiting sea level O_2 to < 60% in inspired gas for the RAF and USAF. The United States Navy (USN) has employed 100% O_2 in combat aircraft. Ostensibly, this is to provide protection against toxic fumes and against drowning upon entry into the water via a crippled aircraft or parachute. To date no studies have shown a benefit of this strategy in comparison to the deleterious effects of acceleration atelectasis.

No long-term deleterious effects have been previously found if acceleration atelectasis develops repeatedly in flight. The re-inflation with deep breathing or coughing is effective in reversing the atelectasis once breathing air at sea-level pressures post flight. The chest discomfort and the coughing make this condition unacceptable. If coughing occurs during dynamic flight it can over pressurize lung segments causing alveolar damage. Also, if the inhaled gas drops significantly, this can worsen the right to left shunt (hypoxia) as a significant portion of the lung can be utilized to compensate for the drop in O_2 partial pressure.

Hyperoxia (Excessive O_2)

A principle concern and area of special mention to be emphasized is hyperoxia in the aviation environment. It has been continually found that there are widespread misconceptions on the use of high concentrations in the aviation environment. (Note the Hyperoxia section is heavily referenced due to the distinct sections of medical evidence). The result of using high concentrations of inhaled oxygen (high FiO_2) is DAA – Denitrogenation Absorption Atelectasis. As noted in the previous section, nitrogen in the alveoli will be washed out and replaced with O_2 with high concentrations of O_2 are respired. O_2 is extremely soluble and in blood and attaches rapidly to hemoglobin and thus diffuses rapidly in the pulmonary circulation. Not enough gas remains in the alveoli to maintain patency and the alveolus collapses. (Lumb Ab, ed Nunn's Applied Respiratory Physiology, 6th edition. Philadelphia PA, Butterworth-Heinemann/Elsevier, 2005; Déry, R, Pelletier J, Jacques A, Clavert M, Houde J, Aveolar Collapse induced by denitrogenation. Can Anaesth Soc J. 1965, 12(6): 531-557). A contributing mechanism occurs if the inspired VA/Q ratio of a lung unit is reduced, a point is reached where the rate at which inspired gas entering the alveolus is exactly balanced by gas uptake from the alveolus into the blood. This point is known as the critical flow rate (VA/Q) ratio. If the inspired VA/Q ratio is less than this, the lung unit will collapse. This is likely when FiO_2 is high and the gas uptake is large. Anesthesia literature has shown that when an FiO_2 of 100% is used after a VCM (Vital Capacity Maneuver), atelectasis recurs within 5 min. Recurrence of atelectasis within five min after a vital capacity maneuver at FiO_2 = 100% or immediately after removal of positive-end expiratory pressure (PEEP) at FiO_2 = 40% suggests an instability in the alveoli that have been collapsed. It is possible that atelectasis, once formed, impedes surfactant function so that such a region is prone to collapse again after having been reopened. On the other hand, when 40% O_2 is used, atelectasis will not recur for at least 40 min. In order to avoid atelectasis formation, lower O_2 concentration has been used during induction of general anesthesia. With 100% O_2, shunt increased from 0.3% to 6.5%, with atelectasis formation corresponding to an area of 8.0 cm^2. With 30% oxygen, shunt increased to only 2.1%, with minimal atelectasis (0.2 cm^2). Without any pre-oxygenation, no atelectasis was seen directly after induction. In contrast if the FiO_2 was increased to 100% before intubation, atelectasis appeared. Moreover, increasing FiO_2 at the end of surgery to 1.0 before extubation increased atelectasis formation, which persisted in the postoperative period. (L. Magnusson and D. R. Spahn. New concepts of atelectasis during general anesthesia. British Journal of Anaesthesia 91 (1): 61±72 (2003). David C. Warltier, M.D., Ph.D., Editor. Pulmonary Atelectasis. Anesthesiology 2005; 102:838–54. Lena E. Andersson et al. Effect $O_2$of Carbon Dioxide Pneumoperitoneum on Development of Atelectasis during Anesthesia, Examined by Spiral Computed Tomography. Anesthesiology 2005; 102:293–9. Atelectasis during Anesthesia: Pathophysiology and Treatment. Rev Bras Anestesiol 2008; 58: 1: 73-83. Raquel S Santos, Pedro L Silva, Paolo Pelosi, Patricia RM Rocco. Recruitment maneuvers in acute respiratory distress syndrome: The safe way is the best way. World J Crit Care Med 2015 November 4; 4(4): 278-286. Hedenstierna G[1], Rothen HU. Atelectasis formation during anesthesia: causes and measures to prevent it. J Clin Monit Comput. 2000; 16(5-6):329-35)

1) Since the partial pressures of gasses decrease in ascent to altitude, the denitrogenation occurs faster. The effects on vital capacity were demonstrated in the Royal Australian Air Force (RAAF) document #D18123622 submitted to the root cause corrective action (RCCA) Aerospace Medicine and Physiology Team. Vital capacity was reduced by a further 15% after flight, to an average of 28% below baseline (but as much as 35% in some cases). In aviation it is known that hyperoxia has resulted in complaints of sough, dyspnea, and chest pain in aviator's flying at altitudes between 14,000 and 20,000 ft for 5 hours or longer. (Gradwell DP**.** Prevention of hypoxia. In: *Ernsting's Aviation Medicine*, edited by Rainford DJ, Gradwell DP. London: Hodder Arnold, 2006, p. 57–71, C. Dussault, E Gontier, C. Verret, M. Soret, A. Boussuges, G. Hedenstierna, X S. Montmerle-Borgdorff, Hyperoxia and hypergravity are independent risk factors of atelectasis in healthy sitting humans: a pulmonary ultrasound and SPECT/CT study, *J Appl Physiol, 2016,* 121: 66–77). Dussault et al. revealed that when breathing 100% O_2, high-grade atelectasis was present by computerized tomography (CT) and was manifested by cough and chest pain. After inhaling only 44.5% O_2, only a small-grade atelectasis was visualized and not manifested by frank symptoms. Dassault also found that acceleration and absorption atelectasis are independent of one another i

2) There are numerous deleterious effects of hyperoxia on the cardiovascular system.

a. Smit et al. in a multivariate analysis of 85 studies, found that arterial hyperoxia induced various amounts of vasoconstriction peripherally. The magnitude of the constriction was proportional to the level of inhaled O_2 and prominent in vessels ~15 to 25 μm in diameter. Pronounced constriction was seen in muscle vasculature, while constriction was seen in the skin and intestines was not as prominent.(Smit B, Smulders Y, Eringa e, Oudemans-van Straaten H, Girbes A, Wever K, Hooijmans C, Spoelstra A, Effects of hyperoxia on vascular tone in animal models: systematic review and meta-analysis, *Critical Care*2018, **22**:189, pp1-16). Thompson et al. found that One Hour of Hyperoxia with isocapnea increased systemic vascular resistance index (SVRI), reduced Heart Rate, Cardiac Index, and stroke index (SI). The effects on SVRI and Cardiac Index persisted for up to 1 hour after normoxic inhalation. Numerous other studies have shown similar effects. (Asmussen E and Nielsen M. The cardiac output in rest and work at low and high O_2 pressures. *Acta Physiol Scand* 35: 73–83, 1955. Daly WJ and Bondurant S. Effects of O_2 breathing on the heart rate, blood pressure and cardiac index of normal men — resting, with reactive hyperemia, and after atropine. *J Clin Invest* 41: 126–132, 1962. Haque WA, Boehmer J, Clemson BS, Leuenberger UA, Silber DH, and Sinoway LI. Hemodynamic effects of supplemental O_2 administration in congestive heart failure. *J Am Coll Cardiol* 27: 353–357, 1996. Whitehorn WV, Edelmann A, and Hitchcock FA. The cardiovascular responses to the breathing of 100% O_2 at normal barometric pressure, *Am J Physiol* 146: 61–65, 1946). Two other studies have shown these cardiovascular effects and that persistent increased peripheral vascular resistance remained for 30 to 40 minutes after being placed on normal 21% O_2. (Eggers GWN, Paley HW, Leonard JJ, and Warren JV. Hemodynamic responses to O_2 breathing in man. *J Appl Physiol* 17: 75–79. 1962. Waring WS, Thomson AJ, Adwani SH, Rosseel AJ, Potter JF, WebbDJ, and Maxwell SRJ. Cardiovascular effects of acute O_2 administration in healthy adults. *J Cardiovasc Pharmacol* 42: 245–250, 2003.) Waring et al. pointed out that the arterial and venous saturations were 85% and 86% respectively in their studies.

There are peripheral circulation disturbances also notes with high FiO_2 inhalation. Orbegozo et al. found that normobaric hyperoxia significantly altered microcirulation in healthy individuals. They found that this decreased the proportion of perfused vessels (PPV) from 92% to 66%, perfused vessel density (PVD) from 11.0 to 7.3 vessels/mm, perfused small vessel density (PSVD) from 9.0 to 5.8 vessels/mm and microvascular flow index (MFI) from 2.8 to 2.0, and increased PPV heterogeneity from 7.5% to 30.4%. Muscle oxygen consumption (VO_2) decreased from 8.5 to 7.9%/s. Thirty minutes after return to air, PPV, PVD, PSVD and MFI remained partially altered. Normobaric hyperoxia alters the microcirculation in healthy subjects, decreasing capillary perfusion and VO_2. (Diego Orbegozo Corté, FlorinPua, Katia Donadello Fabio SilvioTaccone LeonardoGottin[b] JacquesCreteur[a] Jean-Louis Vincent[a] Daniel De Backer, Normobaric hyperoxia alters the microcirculation in healthy volunteers, Microvascular Research, Vol 98, March 2015, Pages 23-28)

b. Seals et al. demonstrated that breathing 100% O_2 can decrease sympathetic activity (Seals DR, Johnson DG, Fregosi RF. Hyperoxia lowers sympathetic activity at rest but not during exercise in humans. Am J Physiol. 1991b;260:R873–878), Specifically they showed that in healthy humans, hyperoxia lowered the efferent sympathetic nerve activity to skeletal muscle under resting conditions but it did not have an obvious modulatory effect on the nonactive muscle sympathetic nerve adjustments to rhythmic exercise.

c. Hyperoxia has been found to decrease cardiac output and raises systemic vascular resistance (Whalen RE, Saltzman HA, Holloway DH, Jr, McIntosh HD, Sieker HO, Brown IW., Jr Cardiovascular and blood gas responses to hyperbaric oxygenation. Am J Cardiol. 1965; 15:638–646. Mak S, Azevedo ER, Liu PP, Newton GE. Effect of hyperoxia on left ventricular function and filling pressures in patients with and without congestive heart failure. Chest. 2001;120:467–473, Mak S, Egri Z, Tanna G, Colman R, Newton GE. Vitamin C prevents hyperoxia-mediated vasoconstriction and impairment of endothelium-dependent vasodilation. Am J Physiol Heart Circ Physiol. 2002; 282:H2414–H2421.

Reinhart K, Bloos F, Konig F, Bredle D, Hannemann L. Reversible decrease of O_2 consumption by hyperoxia. Chest. 1991; 99:690–694).

3) Breathing high concentrations of O_2 can lead to impaired O_2 exchange (Aboab J, Jonson B, Kouatchet A, Taille S, Niklason L, Brochard L. Effect of inspired O_2 fraction on alveolar derecruitment in acute respiratory distress syndrome. Intensive Care Med. 2006; 32:1979–1986, Dantzker DR, Wagner PD, West JB. Instability of lung units with low VA/Q ratios during O2 breathing. J Appl Physiol. 1975; 38:886–895).

4) Hyperoxia has resulted in cerebral blood flow decreases and metabolic rates. As early as 1947 there were indication that cerebral blood flow was inhibited by high concentrations of O_2. Kety et al. showed that FiO_2 inhaled in concentrations of 85 to 100% was associated with a reduction in cerebral blood flow of 13%. They showed that a FiO_2 of 10% O_2 produced an increase of 35% in Cerebral Blood Flow (CBF). Research since that time has revealed that inhaling high concentrations of O_2 results in decreases in cerebral metabolic rates (Xu F, Liu, P, Pascual JM, Xiao G, Lu H, Effect of hypoxia and hyperoxia on cerebral blood flow, blood oxygenation, and oxidative metabolism, Jou Cerb Blood Fl and Met, Oct 2012, p 1909-1998), decreased CBF (Watson NA, Beards SC, Altaf N, Kassner A, Jackson A. The effect of hyperoxia on cerebral blood flow: a study in healthy volunteers using magnetic resonance phase-contrast angiography, Eur J Anaesthesiol, 2000, vol. 17 (pg. 152-9)). Breathing high concentrations of O_2 can lead to impaired O_2 exchange (Aboab J, Jonson B, Kouatchet A, Taille S, Niklason L, Brochard L. Effect of inspired O_2 fraction on alveolar derecruitment in acute respiratory distress syndrome. Intensive Care Med. 2006; 32:1979–1986, Dantzker DR, Wagner PD, West JB. Instability of lung units with low VA/Q ratios during O_2 breathing. J Appl Physiol. 1975; 38:886–895). Xu demonstrated that hyperoxia decreased cerebral metabolic rate of oxygen ($CMRO_2$) by 10.3±1.5% ($P < 0.001$) with using 50% inhaled O_2 and 16.9±2.7% ($P < 0.001$) for FiO_2 of 98%. Hyperoxic-induced vasoconstriction is variable and has been shown to decrease cerebral blood flow from 9 to 31% (Watson et al.) and up to 40% by Decker et al. (Decker, ASMA presentation, Effects of Hyperoxia on MRI and EEG, Aerospace Medicine Association Meeting, Dallas Texas. June 7, 2018. Article Pending.) Certain areas of the brain may be more susceptible to hyperoxia than other areas. Exercise increases CBF but it was found that with hyperoxia, the middle cerebral artery did not increase in flow, whereas the posterior cerebral artery did with exercise. (Smith KJ, Ainslie PN, Regulation of Cerebral Blood Flow and Metabolism during Exercise, Exper Phys, 1 Nov 2017, Vol 102, Iss 11, pp 1356-1371, Smith, K.J., Wong, L.E., Eves, N.D., Koelwyn, G.J., Smirl, J.D., Willie, C.K., & Ainslie, P.N. (2012). Regional cerebral blood flow distribution during exercise: Influence of O_2. Respir Physiol, Neurobiol, 184(1), pp.97-105). The reduced CBF restricts the excessive amount of O_2 going to the brain, as the metabolic processes should be supported by the excess O_2. Xu et al. (Feng Xu, Peiying Liu, Juan M Pascual, Guanghua Xiao, and Hanzhang Lu, Effect of hypoxia and hyperoxia on cerebral blood flow, blood oxygenation, and oxidative metabolism. J Cereb Blood Flow Metab. 2012 Oct; 32(10): 1909–1918) pointed out that when exposed to 98% oxygen the cerebral metabolism decreased by about 17%. Due to the vasoconstriction and decreased cerebral metabolism, a vulnerable state is induced in the brain. Bulte et al. reported (Bulte DP, Chiarelli PA, Wise RG, Jezzard P. Cerebral perfusion response to hyperoxia. J Cereb Blood Flow Metab. 2007; 27:69–75) observing regional perfusion of grey matter even at moderate levels of hyperoxia; however, perfusion changes at all O_2 levels were relatively mild. Nishimura used stepwise increases in FiO_2 to 40%, 70%, and 100%. The measured End-tidal carbon dioxide (CO_2) decreased significantly at 70% and 100% O_2. Steady-state cewrevral blood flow velocity (CBFV) decreased significantly at FiO_2 at or above 40%, while mean arterial blood pressure (MBP) was unchanged. Associated with these changes, cerebral vascular resistance index increased at 70% and 100% O_2. This indicated that even during mild hyperoxia, reduction in steady-state CBFV occurs. (Nishimura N, Iwasaki K, Ogawa Y, Shibata S. Oxygen administration, cerebral blood flow velocity, and dynamic cerebral autoregulation. Aviat Space Environ Med. 2007; 78:1121–1127).

5) Changes in neural activity are not delineated by indirect measures using functional magnetic resonance imaging (fMRI), Positron Emission Tomography, or functional optical imaging. These studies delineate the vascular effects hyperoxia, but not the neural activity. The assumption has always been that the excess O_2, despite vasoconstriction and down regulation of cerebral metabolism, does not alter neuronal function. Xu et al. measured the cerebral metabolic rate of oxygen ($CMRO_2$) and observed decreases in $CMRO_2$ as previously mentioned. Electroencephalography (EEG) studies have shown significant EEG disturbances. Croal et al. used magnetoencephalography (MEG) and observed a moderate reduction (3 to 5%) in occipital lobe signal power. They showed focal decreases in oscillatory power across the alpha, beta and low gamma bands. Interestingly enough was the fact that the T_1 imaging in this study did not show isocapnic hyperoxia had a significant effect on carotid blood flow. (Croal PL, Hall EL, Driver ID, Brookes MJ, Gowland PA, Francis ST (2015), The effect of isocapnic hyperoxia on neurophysiology as measured with MRI and MEG. Neuroimage 105: 323–331) Shen et al. demonstrated in healthy subjects that resting EEGs had significant alterations. The testing was done with resting state and task evoked states and compared to Sham controls. They showed hyperoxia suppressed α (8 to 13 Hz) and β (14 to 35 Hz) band power (by 15.6 ± 2.3% and 14.1 ± 3.1%, respectively), but did not change the δ (1 to 3 Hz), θ (4 to 7 Hz), and γ (36 to 75 Hz) bands. Thus, the statements of hyperoxia has a pronounced effect on brain neural activity. (Sheng M, Liu P, Mao D, Ge Y, Lu H, The impact of hyperoxia on brain activity: A resting-state and task-evoked electroencephalography (EEG) study, PLoSONE 12 (5): e0176610: https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0176610&type=printable). Decker et al. also reported the α and β decreases in correlate with the fMRI decreases in CBF. Wesly and associates studied the effects of short term (15 minute) exposures of 100% O_2. (Wesley Vuong, Sayeed A.D. Kizuk, Joanna MacLean, Clayton T Dickson, Kyle Mathewson, Electrophysiological correlates of hyperoxia during resting-state EEG in awake human subjects, https://doi.org/10.1101/355941). The results showed again an increased blood-O_2 saturation levels, decreased heart rate, and a slight, non-significant, decrease in breathing rate. There were significant neuronal activity changes including decreases in low-alpha (7 to10 Hz), high-alpha (10 to 14 Hz), beta (14 to 30 Hz), and gamma (30 to 50 Hz) frequency ranges during eyes-opened hyperoxic conditions. Paradoxical changes in eyes-closed hyperoxia, increased in the delta (0.5 to 3.5 Hz) and theta (3.5 to 7 Hz) frequency bands were apparent together with decreases in the beta range. The decreased alpha in eyes opened is often associated with increased attentional processing, but the changes in delta and theta indicated an induction of a sleep state. These results suggested a state-specific and perhaps opposing influence of short-term hyperoxia.

6) The Retinal Artery has been shown to have distinct impact with Hyperoxia. Wangsa-Wirawan et al. showed significant constriction of retinal vessels and a reduction in retinal blood flow with inhalation of 100% O_2. This is in order to maintain a normoxic retinal profile of the retinal neurofiber layers. (Norbert D. Wangsa-Wirawan, PhD; Robert A. Linsenmeier, PhD Retinal Oxygen Fundamental and Clinical Aspects, Arch Ophthalmol; 2003, 121 (4) pp54-557). This can be concerning as high concentrations of O_2 in combination with high levels of illumination can damage photoreceptors. (Ruffolo JJ JrHam WTMueller HAMillen JE Photochemical lesions in the primate retina under conditions of elevated blood O_2 .Invest Ophthalmol Vis Sci 1984; 25893-898, Jaffe GJIrvine RWood ISSeveringhaus JWPino GRHaugen C Retinal phototoxicity from the operating microscope Ophthalmology; 1988; 951130-1141). Another significant change was noted that during hyperoxia there was a large increase in choroidal PO_2. This increase is a consequence of the lack of metabolic regulation of choroidal blood flow Huan et al. also demonstrated that with 80% inhaled O_2 there was a significant reduction in retinal perfused vessel density. The reduction was greatest in the macular area than in the peripapillary area. They also demonstrated no real change in flow at the foveal avascular zone. (Huan Xu; Guohua Deng; Chunhui Jiang; Xiangmei Kong; Jian Yu; Xinghuai Sun, Microcirculatory Responses to Hyperoxia in Macular and Peripapillary Regions Investigative Ophthalmology & Visual Science August 2016, Vol.57, 4464-4468.) It was once theorized that hyperoxia may play a part in treating retinal conditions. A fundamental misconception countering that premise is that the O_2 supply to the tissue relies on O_2 saturation. This is an incorrect premise as in reality, O_2 moves into tissue by simple diffusion. This is driven by gradients of PO_2, not saturation. The PO_2 gradient from the choroid is much steeper during hyperoxia, and thus results in a greater portion of the retina can be supplied by the choroid during hyperoxia than during normoxia. This oxygenation occurs despite the retinal reduction in blood flow. Another concern lies in the fact that hyperoxia can be damaging to photoreceptors if combined with high levels of illumination. (Ruffolo JJ JrHam WTMueller HAMillen JE Photochemical lesions in the primate retina under conditions of elevated blood O_2. Invest Ophthalmol Vis Sci. 1984; 25893- 898 .Jaffe GJIrvine RWood ISSeveringhaus JWPino GRHaugen C Retinal phototoxicity from the operating microscope. Ophthalmology. 1988; 951130- 1141).

7) Recent clinical concerns have been raised about the use of normobaric or hyperbaric O_2. Analysis of emergency department and Intensive Care Unit (ICU) patients has shown that outcomes are significant worse in patient with elevated levels of O_2. Several papers point to the fact that Emergency Department hyperoxia is an independent predictor of hospital mortality. Most of the multivariate studies focus on patients with hyperoxia in the first 24 to 48 hours of admission. Animal studies have shown that the deleterious effects of hyperoxia are both time and dose dependent. These animal models have shown that only a few hours of hyperoxia provoke pathologic changes in pulmonary mechanics and deleterious inflammatory changes. Stolmeijer et al. conducted a clinical literature review of hyperoxia in acutely ill patients. The outcomes of neurological and functional states as well as mortality were examined. Only one study showed a transient improvement in traumatic brain injury, other studies revealed higher mortality rates after cardiac arrests, cerebrovascular accidents (CVAs), and traumatic brain injuries. (R. Stolmeijer , H. R. Bouma, J. G. Zijlstra, A. M. Drost-de Klerck, J. C. ter Maaten, and J. J. M. Ligtenberg, A Systematic Review of the Effects of Hyperoxia in Acutely Ill Patients: Should We Aim for Less? BioMed Research International Volume 2018, Article ID 7841295, 9 pages

8) Breathing 100% O_2 is well known to cause the development of delayed otic barotrauma or barotitis. This can occur in moderate ascent to and descent from altitude. The usual course is that the aircrew member will awaken the next day after the flight or altitude chamber run with ear pain and moderate deafness. Physical examination reveals the tympanic membrane (TM) (ear drum) is drawn inwardly towards the middle ear and this usually contains fluid. The deafness and discomfort can be relieved by introducing air into the middle ear. This is done by Frenzel's maneuver or Valsalva maneuver. The mechanisms for barotrauma from excessive O_2 are similar to the G induced atelectasis. With the use of 100% O_2 the nitrogen is washed out of the middle ear and replaced with O_2. The capillaries rapidly absorb the O_2 and this reduces the pressure in the middle ear. The TM is pulled into the middle ear cavity resulting in pain and deafness. If numerous ascents to altitude have been performed (even to 5,000 ft) on 100% O_2 without reintroduction of nitrogen, a painful retraction of the TM occurs. Also, if a rapid change in altitude or frequent changes in altitude occur whether with or without 100% O_2, and the middle ear is not allowed to compensate for the changes, then a painful barotitis occurs. This condition is amplified with breathing 100% O_2. In this case both breathing > 60% O_2.

Standards for Aircraft

In the development of standards, the prevention of absorption and accentuated acceleration atelectasis and traumatic barotitis were crucial in highly dynamically maneuvering aircraft. The standards were established for the RAF and USAF from the 1950s to the 1990s to keep the concentration of O_2 should not exceed 60%. There are limits to the altitude range that this can be applied. As altitude increases the concentration of O_2 must be increased to prevent hypoxia, which is of critical importance. There are factors that must be taken into consideration to adjust the maximum amount of O_2 in relation to the cabin altitude. The first factor to consider is the pressurization schedule of the aircraft. The aircrew should only be exposed to cabin altitudes greater than 20,000 to 25,000 ft in the case of a decompression of the cabin. These are rare events, but the risk increases in combat operations. The primary goal is preventing Decompression Sickness. The next factor to consider is the effect of high levels of G forces.

Many combat aircraft cannot maintain $+G_z$ accelerations greater than about 3 to 4 G at altitudes above 36,000 ft. This limits the amount of acceleration atelectasis that occurs at these altitudes. This should equate to cabin altitudes $\geq$ 15,000 ft. The next factor to consider is that it is technically difficult to match the narrow physiological limits if the O_2 concentration is not allowed to exceed 60% at altitudes greater than 15,000 ft. The <u>minimum</u> concentration of O_2 at a cabin altitude of 18,000 ft is 49%. (Figure 1). Above 30,000- to 33,000-ft cabin altitude, 100% O_2 is required to maintain alveolar O_2 concentration greater than 103 mmHg. Above 40,000 ft, positive pressure for breathing (additional pressure provided to the mask with the O_2) is required to maintain the alveolar O_2 partial pressure.

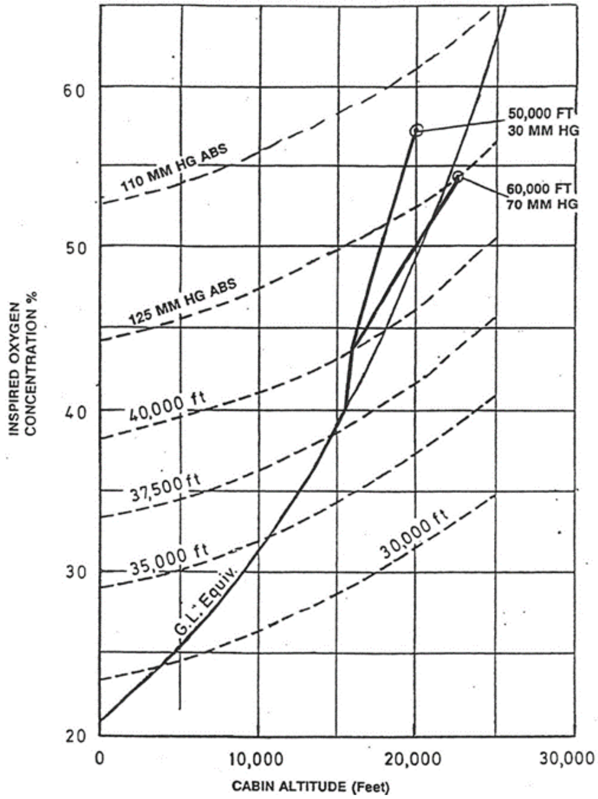


Figure 1

From: *Raising the Operational Ceiling, Proceedings of a Workshop held at Armstrong Laborator*y, Brooks AFB, 13-15 June 1995

Relationship between concentration of O_2 in the inspired gas and the pressure altitude within the cabin required to:

1) Maintain an alveolar PO_2 of 103 mmHg
2) Produce an alveolar PO_2 of 30 mmHg on an instantaneous decompression from the cabin altitude denoted on the X axis to the cabin altitude/absolute intrapulmonary pressure denoted by the broken horizontal curves [final cabin altitudes or 30, 35, 37.5 and 40 thousand ft and final intrapulmonary absolute pressures of 141 mmHg (40,000 ft Curve) 125, and 110 mmHg] This is the minimum concentration of O_2 to prevent hypoxia on a subsequent rapid decompression from the altitude of flight. An alveolar PO_2 of $\leq$ 30 mmHg, even for a few seconds will result in unconsciousness.

3) Ensure with a cabin pressure differential of 5 Lb. in^2, that an instantaneous decompression form the cabin altitude on the X axis the alveolar PO_2 immediately after the decompression will be 30 mmHg when
    a. using a pressure breathing system which provides a breathing pressure of 30 mmHg at 50,000 ft and
    b. using a pressure breathing system which provides a breathing pressure of 70 mmHg at 60,000 ft

Combining all the relationship to the cabin altitude, the scheduling of the cabin, the G forces involved, and the technical difficulties lead to the limitation should not exceed 60% O_2 from ground level to 15,000-ft cabin altitude. This limit should not exceed 75% O_2 from 15,000 to 20,000 Ft cabin altitude. These requirements were incorporated into Air Standards 61/101/6A and STANAG 3865. (Figure 2).

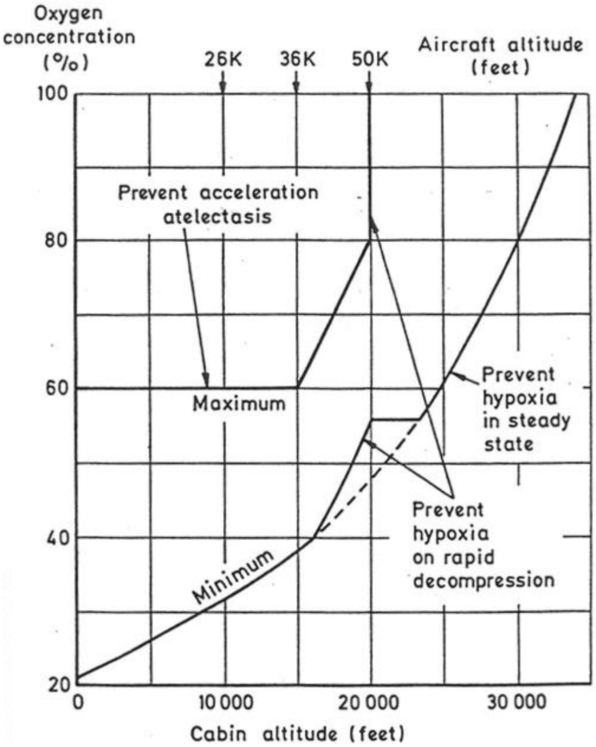


Figure 2. Relationships between minimum and maximum concentrations of O_2 in inspired gas and the cabin altitude with the cabin pressurized for a typical agile combat aircraft with a ceiling of 50,000 ft.

From: *Raising the Operational Ceiling, Proceedings of a Workshop held at Armstrong Laborator*y, Brooks AFB, 13-15 June 1995.

As an example of not addressing physiological standards, for the F-22, the normal standards in design and development were not followed. The USAF found that through early 2012, there had been an increasing number of hypoxia-like incidents in the F-22 Raptor. This was surmised as being related to the On-Board Oxygen Generating System (OBOGS) or its installation. There were numerous concerns raised by the USAF Safety Accident Boards and the NASA Investigation into the F-22 investigation of the incidents. These findings were summarized in the

USAF Scientific Advisory Board Report on Aircraft Oxygen Generation, February 1, 2012. dsp.dla.mil 31.

1) An applicable multi-national standardization document from the Air and Space Interoperability Council (ASIC; formerly Air Standardization Coordinating Committee)—currently ASIC Advisory Publication 4060, 'The Minimum Quality Criteria for On-Board Generated Oxygen'—was called out as advisory guidance for the F-22.

2) The USAF substantially diminished its application of systems engineering and reduced its acquisition core competencies (e.g., systems engineering, human systems integration (HIS), aviation physiology, cost estimation, contracting, and program and configuration management).

3) Lost capabilities and expertise to perform the critical function of HSI led to atrophy of policies/standards and research and development expertise with respect to the integrity of the life support system.

4) Three life support system-critical subsystems (OBOGS, Back-up Oxygen System [BOS], and Emergency Oxygen Subsystem [EOS]) were not classified as "safety-critical items" and were integrated or eliminated without sufficient analysis.

5) Modeling, simulation, and integrated hardware-in-the-loop testing to support the development of the F-22 life support system and the thermal management system were insufficient to provide an 'end-to-end' assessment of the range of conditions likely to be experienced by the F-22.

6) The OBOGS was developed as a "fly-to-warn/fail" system with no requirement for initial or periodic end-to-end certification of the breathing air or periodic maintenance and inspection of key components." This led to the development and implementation of " …a comprehensive Aviation Breathing Air Standard to be used in developing, certifying, fielding, and maintaining all aircraft oxygen breathing systems."
(http://www.dsp.dla.mil/Portals/26/Documents/Publications/Journal/160301-DSPJ-06.pdf)

These were incorporated into the Military Standard (MIL-STD) 3050 document. "For fighter and trainer aircraft the O_2 concentration delivered by the breathing system using OBOGS shall be above the O_2 warning threshold at steady-state breathing gas flows from 7 to 60 liters/minute/crew member Ambient Temperature and Pressure Dry (ATPD) from Sea Level to a cabin altitude of 7,999 feet; and 2) 7 to 80 liters/minute/crew member (ATPD) from a cabin altitude of 8,000 feet to the aircraft maximum ceiling. (NOTE: If the breathing system using OBOGS will supply O_2 to a demist system, for example as part of a chemical defense ensemble, the steady-state flow should be increased accordingly.) The system shall be capable of achieving peak inspiratory and expiratory flows of up to 4.3 liters/sec ATPD (258 L/min ATPD)" and"…the concentration of oxygen in the inspired gas shall not exceed 60% at cabin altitudes between 0 and 15,000 ft or 75% at a cabin altitude of 20,000 feet, except momentary excursions…" This again reinforces the findings that have been made historically by aviation physiology studies. The reports did address some of the physiological issues, but there were many open items not addressed. This study's findings accelerate closing the knowledge gaps on many questions.

The above background makes it imperative that this be reflected in any standards going forward. The Aircrew Breathing study has delineated breathing system dysfunctions that compound the effects of aviation in the normal and dynamic regimes. It would seem that in aircraft programs problems that affect the performance of the human through the human-machine interface have either not been identified early in the design phases, and/or have not been acted upon once discovered. There is no doubt that the twin pressures of budget and schedule exert a tremendous force in the programmatic management of any large-scale system. And based on the fundamental human research performed by the military and others over the years gone by, it is tempting to think that all of the human performance requirements for a given system are known, thereby rendering further funding for human testing and design change unnecessary. Yet when assumptions on human performance are made, designers may not realize where these assumptions are not completely valid. That is, if the assumptions underlying requirements are incorrect and/or are based on an incomplete understanding of human physiology, then such assumptions can be very costly in the long run. The continuing belief that Hyperoxic concentrations of O_2 seem to validate these misunderstandings. There must be requirements established to adequately meet the actual demands of aircrew. Furthermore, subsequent changes to the aircraft that can affect the human within this system; however, there has to be significant effort to re-assess the human design requirements or to determine if those requirements actually meet the current demands of the aircrew operating the system. In short, there must be a HSI process. These are findings that have been identified in the F/A-18 and F-22 NESC Life Support Systems reviews.

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Appendix 5: Development of JPL Mask

5.1 Structural Integrity Memo

Lance E. Christensen, Jet Propulsion Laboratory

3/9/2019

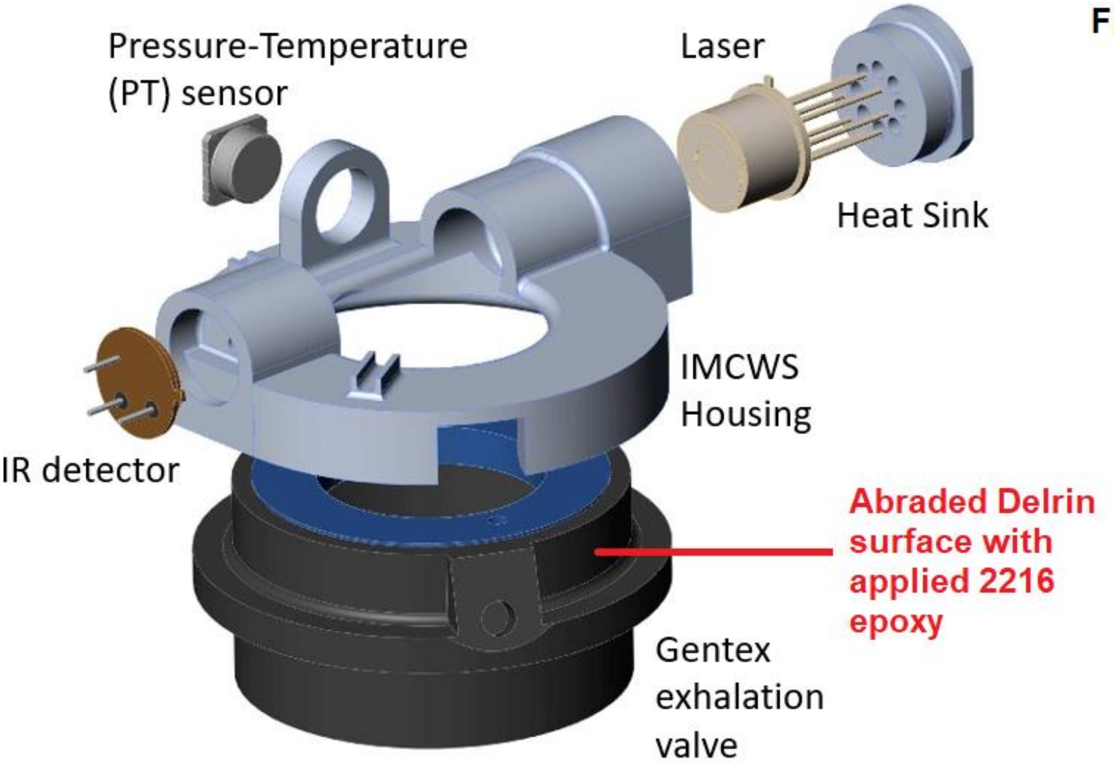
1. Background:

The Jet Propulsion Laboratory (JPL) is constructing, in-house, an in-mask carbon dioxide (CO_2) and water vapor sensor (IMCWS) that uses tunable laser spectroscopy to probe the breathable air of the pilot. Below are specific details regarding the structural components of this sensor. Much of this material was reviewed at the IMCWS design review November 7, 2019.

It should be noted that the entire end-to-end structure, mounted inside the mask with connected wiring, has been subject to a windblast test and rapid decompression test. It passed both tests.

2. Specific bondings and housings

Figure 1



A. Bonding of main sensor body to valve

The Delrin surface of the valve is abraded on the surface as shown above. The matching surface of the aluminum main sensor body is also abraded. Then ScotchWeld Epoxy 2216 A/B is applied to these surfaces as shown in Figure 1. The epoxy is cured over 7 days at room temperature. The total surface area of bonding is 0.5 in^2. The total mass of material on the valve is 35 grams. Using a loading of 40 G, as prescribed by Armstrong Flight Research Center (AFRC) and based on MIL-A-8865 Rev B, outward along the flow axis of the exhalation valve, the force on the adhesive bond due to the IMCWS mass is: 40 (0.077 lb)/.50 in^2 = 6.2 psi.

B. Bonding of Laser and Detector to main sensor body

The laser is first bonded to an aluminum laser mount (gold item in Figure 2) via Epo-Tek H20E epoxy. The threads (7/16-30 UNF (Unified National Fine)) of the aluminum housing are then coated with Solithane 113/300 TYPE B and then the laser mount is screwed in to 2 ft-lb torque. The detector is bonded directly to housing with 2216 epoxy.

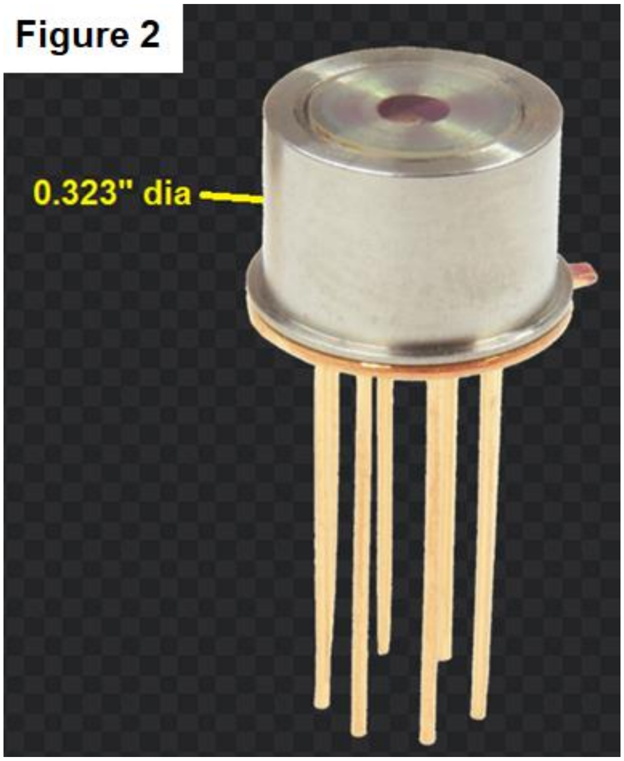


Figure 2

The electrical sockets and wires to the laser and detector are bonded together with housing, sockets and wires via Arathane 5753. The worst-case stress in bond at 40 G is 1.4 psi (detector mass 0.6 g = 0.0013 lb and Bond area = 0.038 in^2).

C. Structural integrity of Laser and Detector

The figure shows the laser, which does have a hermetically sealed inside volume. The detector does not have sealed air volumes.

There is a borosilicate window attached via Nanoplus epoxy to a Kovar housing. JPL conducted two rapid decompression tests and observed that the laser structure (as well as detector) stayed intact. That is, rapid decompression did not affect the laser. The rapid decompression test results are in a separate document.

D. Bonding of pressure sensor to main body

The pressure sensor is bonded with 2216 epoxy to the main body. The rapid decompression test as well as the windblast test demonstrated that all parts of the pressure sensor stayed intact during those tests.

5.2 ICWMS Bill Of Material (BOM): Wetted components

ICWMS BILL OF MATERIAL (BOM): Wetted components

Component part	Material
Sensor Housing	Aluminum
Gentex Exhalation Valve	Delrin Plastic
Laser (hermetically sealed package)	Gold/Nickel Plated Kovar, borosilicate window
Detector	Gold/Nickel plated Kovar
Pressure Transducer	Stainless steel housing, silica gel
PCB Board	Fiberglass FR4
Laser and Detector electrical sockets	Insulator: Hi-Temp UL 94V-O Terminal: Brass, per ASTM-B16 Contact: BeCu, Per ASTM-B19, electroplated NiAu coated
Thermistor	3” Solid Nickel Wire Leads, Teflon Insulation, baked-on phenolic plastic
Solders	SnPb 63/37
Black ink coating on main housing	Enthone M-0-C (aka Warnow Ink)
Wire coatings	ETFE
Glenair connector	Hysol epoxy EE4215 potting compound
Bonding Epoxies	ARATHANE 5753A/B (retains PTFE wires) Scotch Weld EC 2216 A/B (main body to Gentex valve) SOLITHANE 113/300 TYPE B (threads for heat sink to main body) Epo-Tek H20E (laser to heat sink)

5.3 AFRC Laser Evaluation and Recommendation Report

AFRC LASER EVALUATION AND RECOMMENDATION REPORT
INVENTORY NUMBER: IMCWS-Mask

In-Situ Measurements

IN MASK CO2 and WATER VAPOR SENSOR (IMCWS)

January 28, 2020

EXECUTIVE SUMMARY

PURPOSE

An evaluation of the potential safety hazard associated with the **IMCWS (pilot mask)** has been performed by the AFRC Laser Safety Officer. This Instrument will be used during the **various testing in the F-18.**

BACKGROUND:

The **IMCWS** is an equipment with an embedded/totally encased laser that will measure the CO2 and water vapor in a pilot's mask. The IMCWS consists of a Tunable Diode Laser (TDL) emitting at 2683 nm; an infrared detector; a pressure and temperature sensor; and related electronics to control the laser output, to receive and process the detector output, to read the pressure and temperature sensor, and to control the laser thermoelectric cooler.
The laser wavelength tunes over a spectral range that includes distinct CO2 and H2O rovibrational absorption lines. The detector records the power vs wavelength of the laser beam after the beam passes through the gas near the exhalation valve.

The electronics receives the detector signal as input and calculates the concentrations of CO2 and H2O using simultaneously acquired pressure, temperature and sensor measurements. Laser power shall be no greater than 500 uW in the mask volume

The IMCWS will be installed in a Gentex MBU-20/P pilot mask.

Picture of the laser system

RESULT AND RECOMMENDATIONS:

The IMCWS has been classified as a CLASS 1.

The Class 1 Laser System is considered to be incapable of producing damaging radiation levels during the operation and exempt from any control measure. A common example of a Class 1 laser system is one that includes an embedded high-class laser, but during normal operation presents no laser radiation hazard to the user.

"All application of lasers or laser systems where the entire beam path is enclosed and the enclosure fulfills all requirements of a protective housing, the requirements of Class 1 are fulfilled and no further controls are required" (ANSI Z-136.1-2014, Section 4.4.2.7.3)

Spectrometers/Photometers/Nephelometer/Hygrometers are laser and/or fiber optic products that are fully embedded and enclosed within a protective housing case are considered Class 1 embedded laser. The accessible laser radiation in the sample compartment is very low, below the Class 1 MPE or there is no open beam operations. These systems do not result in a hazard to operators, users, ground observers or the public under normal operations.

The instruments will NOT be opened during airborne or ground operations for servicing or alignment or any other reason.

NO Laser Permit is required.

Operator shall follow all manufacturer recommendations for the laser characteristics and operation.

For any additional assistance or questions regarding this laser safety evaluation report, please contact Dr. Miriam Rodón-Naveira, AFRC Laser Safety Officer at 661 276-3647.

5.4 Rapid Decompression Test of In-Mask CO_2 Water vapor Sensor (IMCWS)

Lance E. Christensen, Jet Propulsion Laboratory
2/11/2020

I. Goals

The main goal is to test the IMCWS in a rapid decompression (RD) environment (differential pressure (ΔP) = 5 psia, ≤ 0.1 s) to understand how IMCWS may impact pilot safety in an ejection event. IMCWS consists of a sensor head with a laser and detector and a pressure-temperature sensor as well as a separate vented electronics box that is linked to the sensor head via an electrical cable.

The four components of IMCWS that will be closely studied during this test are the laser, detector, pressure sensor, and electronics box. The laser, detector, and pressure sensor (Figure 1) are within the mask and it is important to verify that they do not break apart to form hazardous pieces (Foreign Object Debris (FOD)) in the event of RD. The electronics box is a potential pressure vessel, even though it is vented. In sum, the principle concerns are:

a) FOD generated by the laser hermetically sealed at 1 atm; in particular, the borosilicate glass front face of the laser package;
b) FOD generated by the detector; in particular, dislodging of the germanium hyper-hemispheric lens over the detector element;
c) FOD from the pressure sensor; in particular, the white porous material over the piezo-transducer;
d) The electronics box which could act as a pressure vessel.

II. Test articles

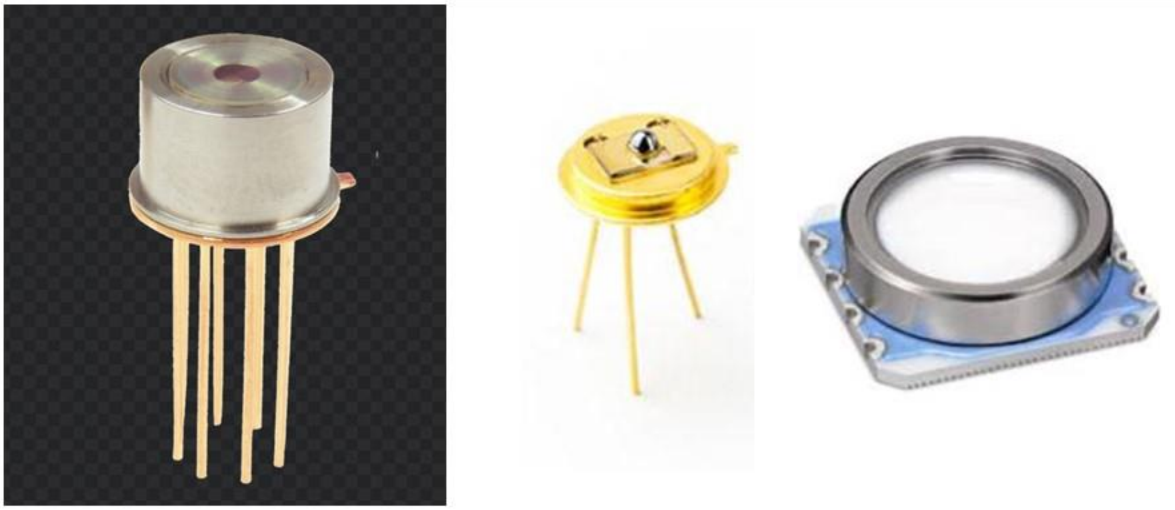


Figure 1. Left: Nanoplus TO-5 laser package. The OD is 8.4 mm. The glass cover is 6 mm dia, 0.6 mm thick. Middle: Vigo PVI-4 detector in TO-39 package (base is 9.2 mm OD); Right: MS5803 pressure-temperature sensor. It is 6.2×6.4mm. The white porous

There are two test articles, as shown in Figure 2.

1) The IMCWS sensor head integrated into a Gentex MBU-20P mask.

2) The IMCWS electronics box which is connected to the IMCWS sensor head via an electrical cable (not shown, not to be tested).

The mask weighs 237 g and is 13 × 10 × 14 cm with integrated IMCWS sensor. The mask contains the aluminum IMCWS sensor head which in turn holds the laser, detector and pressure-temperature sensor. The sensor head weighs 45 g.

The aluminum electronics box weighs 478 g and is 13 × 10 × 4.5 cm. The electronics box has a vent (1/8-NPT, 100-micron 316-ss mesh, max flow 26 scfm at 100 psi). A microSD access port of 1.0- × 1.6-inch surface area was epoxied to the front of the electronics box with Devcon No.14210 5-min epoxy.

The decompression test will be conducted twice. Each test will have a different IMCWS sensor head integrated into its own unique mask: WB#1 and WB#2. Each test will test the same electronics box. Table 1 lists the specific test articles for each test.

Table 1. Test Articles for Rapid-Decompression Tests

	RD Test 1	RD Test 2
Sensor Head/Mask:	WB#1	WB#2
Electronics Box:	Science Box #1	Science Box #1

III. Test procedure

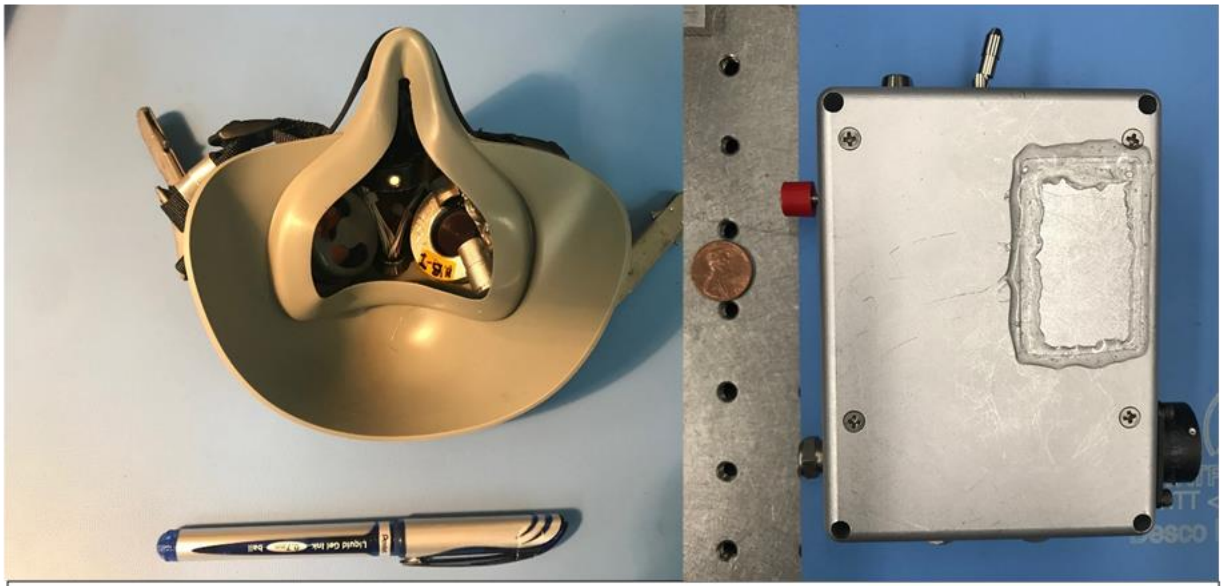


Figure 2. Left: IMCWS sensor head integrated into MBU-20P mask. The sensor head is the aluminum object on the right valve. Right: The IMCWS electronics box (Science Box#1). The SD-disk access port is epoxied into the front of the box as shown.

The test articles will be tested at KBR San Antonio. Test articles are to be placed inside an unoccupied rapid decompression chamber, denoted B-3. The test articles will be unpowered.

Once the articles are placed in the rapid decompression chamber, the pressure-altitude will ascend to 22,000 ft at 5000 fpm, then additionally ascend to 60,000 ft at a rate of 5000 fpm. Once at 60,000 ft, the chamber will be brought back to 22,000 ft at a rate of 5000 fpm. Once at

22,000 ft, the explosive decompression test will be performed where chamber will ascend to 60,000 ft such that 90% of decompression occurred in ≤ 0.1 s. Following this, the chamber will slowly de-pressurize to room pressure at a rate of 5,000 fpm. Cameras outside the chamber will provide information on the performance of the test articles during the pressurizations/de-pressurizations.

III. Test results

Figure 3 documents the pressure-altitude time-series generated from each identical test. A post-test visual inspection was performed with observations documented by JPL.

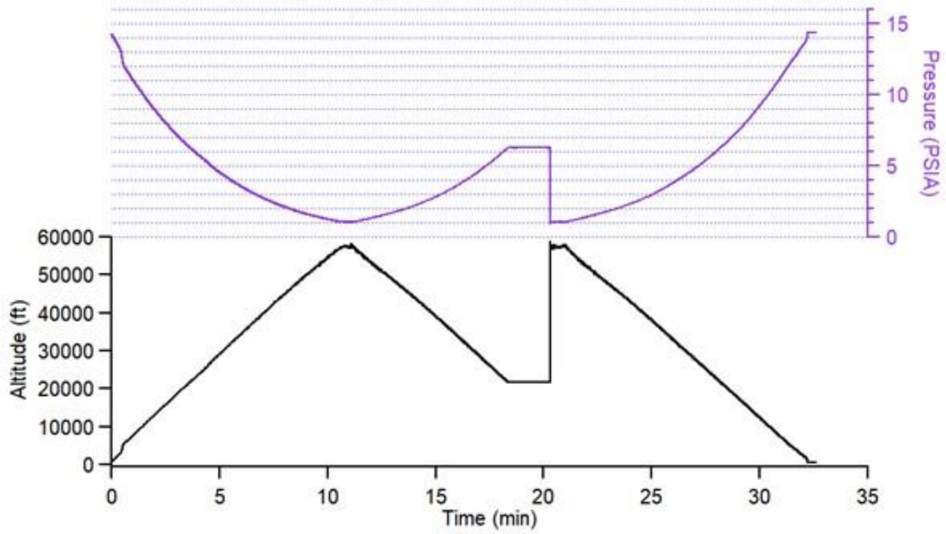


Figure 3. Actual altitude (bottom) and pressure (top) profile for the RD test.

Videos at 25 fps were taken of both RD tests. In addition, Lance Christensen (JPL) watched the test items during the test. Further, after the test was completed, Lance Christensen examined the test items and looked for debris inside the chamber.

Video and visual observation revealed no deformation or FOD generation from the RD. The white porous material covering the MS5803 pressure-temperature sensor remained in place for both optical head units. It is important to note that RD induces mist formation which reduces visibility by around 10 to 20% as can be observed in the video.

There were no FOD within the RD chamber but if FOD were generated, there is chance that it might have been rapidly sucked into the accumulation chamber connected to the RD chamber too quickly to be observed.

The most reliable determination of test results is from post-test examination at JPL on February 8, 2020, and February 10, 2020. This examination included end-to-end powering of both optical heads to determine if the laser/detector system worked the same as prior to the RD test. For WB#1, the optical head worked exactly the same after the RD test as it did before. However, for WB#2, the detector failed to show signal. A second detector was inserted into WB#2, where it was discovered that the laser for WB#2 operated the same as before the RD test.

From visual inspection at JPL of both optical heads, there appears to be no FOD. There appears to be no deformation in either optical head or electronics box. There is no indication of loose material trapped inside the optical heads or electronics box. The detector in WB#2 appears to be intact. It is unclear why the detector on WB#2 does not show signal but it is physically intact.

The conclusions are as follows:

a) The laser package remained intact through RD;
b) The detector package remained intact through RD;
c) The pressure-temperature sensor remained intact through RD;
d) There was no movement, distortion or change in the electronics box through RD.

5.5 Memos

JPL In-Mask CO_2 & Water Sensor (IMCWS)
Memo To Address Hazard Controls for Internal Sensor Components Detaching and Becoming a Choking Hazard
Prepared by John Graf (JSC) and Lance Christensen (JPL)
3/2/20

This memo is written to address one of the Hazards identified as part of the AFRC Tech Brief Assessment of flight testing the JPL In-Mask CO_2 & Water Sensor (IMCWS) as part of the Pilot Breathing Assessment. This memo addresses the hazard that improper design and/or manufacture could result in an internal component breaking loose and presenting a choking hazard. This memo documents the rationale for the project team’s assessment finding and recommendation: the JPL In-Mask Sensor effectively controls the choking hazard and it is safe for AFRC flight test.

This hazard is controlled by:

Limiting the weight of individual components
Securing the components with appropriate adhesives

Hazard controls are verified by:

Checking the integrity of the bonds and adhesives during assembly
Testing structural integrity under worst case survivable load conditions during windblast testing
Testing fracture control integrity under worst cast survivable fracture conditions during rapid depress testing.

Order of magnitude structural analysis results in an assessment that components are small and well secured – the hazard of choking on loose components is well controlled. Windblast testing (the most severe survivable structural load condition) demonstrated structural integrity. Rapid depress testing (the most severe survivable fracture condition) demonstrated component integrity.

The JPL In-Mask has 6 types on internal components. Each component requires a specific assessment. Internal components are:

1. IMCWS Housing
2. Pressure – Temperature Sensor
3. IR Detector
4. Laser
5. Heat Sink
6. Internal Wiring

The largest single component in the IMCWS system that is located inside the mask is the IMCWS structural housing. The Housing is shown in Figure 1 and Figure 3. The IMCWS Housing is bonded to the Gentex Exhalation valve with 3M Scotch-Weld 2216 epoxy. Because the Gantex exhalation valve body is made from Delrin, Scotch-Weld specifications call for an abrade and prime surface prep. AFRC specifies a structural analysis following MIL-A-8865, RevB – this specifies a 40-g inertial load. The mass of the IMCWS housing is less than 35 grams, the bond area between housing and valve is 0.50 in^2, the calculated force on the adhesive bond needs to be 6.2 psi or greater. The rated bond strength of 3M Scotch-Weld 2216 is

1700 psi. The IMCWS housing was tested during windblast testing and bond integrity was demonstrated.

The pressure-temperature sensor has a mass of less than 0.6 gm. The bond area is 0.038 in2. The worst case stress at 40 g is 1.4 psi. The pressure-temperature sensor is bonded using Arathane 5750 or 5753. The rated bond strength of Arathane 5750/5753 is greater than 500 psi. Sensor integrity was tested during windblast testing and bond integrity was demonstrated.

The infrared (IR) detector has a mass of less than 0.6 gram. The bond area is 0.038 in^2. The worst case stress at 40 g is 1.4 psi. The IR detector is bonded using Arathane 5750 or 5753. The rated bond strength of Arathane 5750/5753 is greater than 500 psi. IR detector integrity was tested during windblast testing and bond integrity was demonstrated. The detector has an additional hazard that needs verification of hazard control. The detector has a Gallium Arsenide (GaAs) lens. With sufficient pressure loading the GaAs lens could shatter. The IR detector was subjected to rapid depress testing under greatest survivable pressure load conditions, and fracture control was demonstrated.

The laser is bonded to the aluminum heat sink using Epo-Tek epoxy. The Laser/Heat Sink Assembly is bonded using Arathane 5753. The Laser has a mass of less than 0.6 gram. The bond area is 0.038 in^2. The worst-case stress at 40 g is 1.4 psi. The rated bond strength of Epo-Tek >1200 psi.

The heat sink is bonded to the laser using Epo-Tek epoxy. The Heat Sink / Laser assembly is bonded using Arathane 5753. The heat sink has a mass of less than 0.6 gm. The bond area is greater than 0.038 in2. The worst-case stress at 40 g is 1.4 psi. The rated bond strength of Epo-Tek is >1200 psi.

The internal wiring uses 18-gauge wire. The wire weighs less than 0.6 gram. The tensile strength of 18-gauge wire is 38 lbs per MIL-T-7928. Acceleration loads needed to impart a 38-lb force on less than 0.6 gram of wire are not survivable.

Summary:

The internal components in the IMCWS are robust enough to handle the loads that will be experienced during flight testing without any components becoming dislodged.

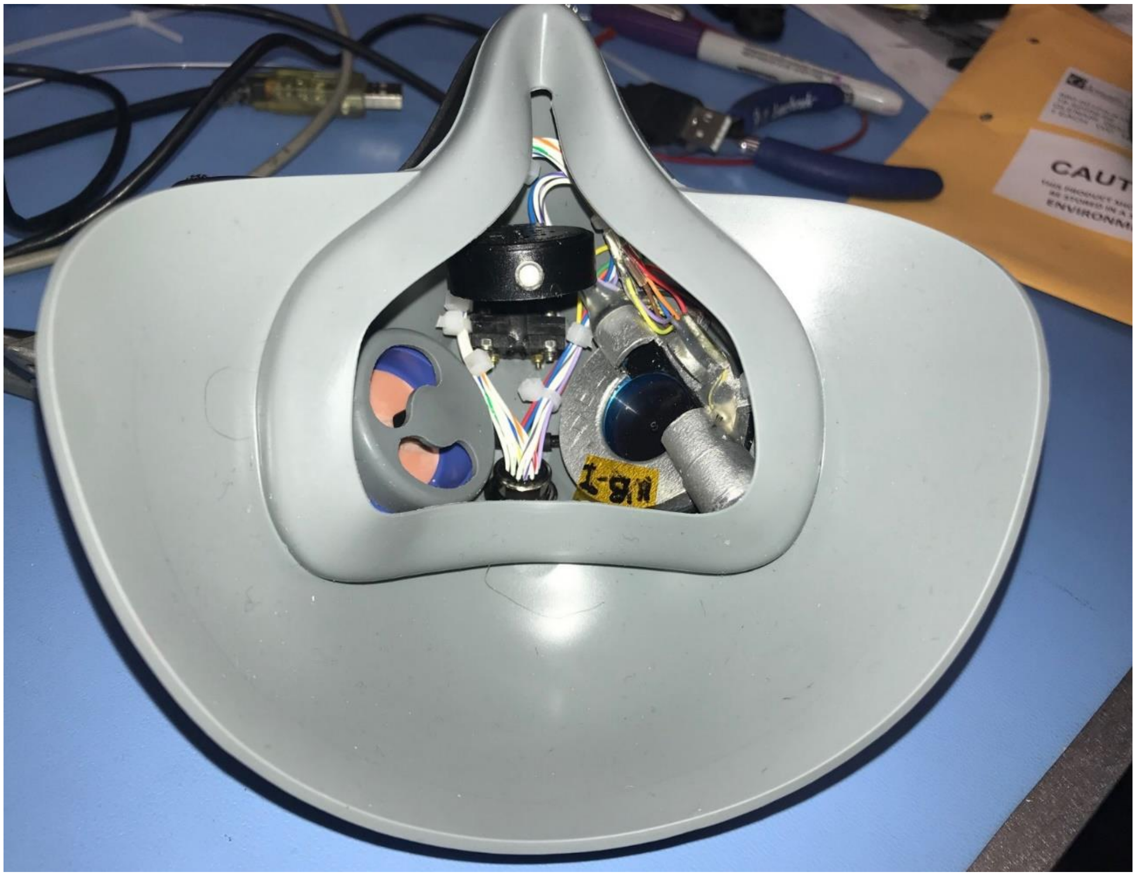


Figure 1: Photo showing internal components

Figure 2 Photo Showing External Power Supply and Connecting Cable

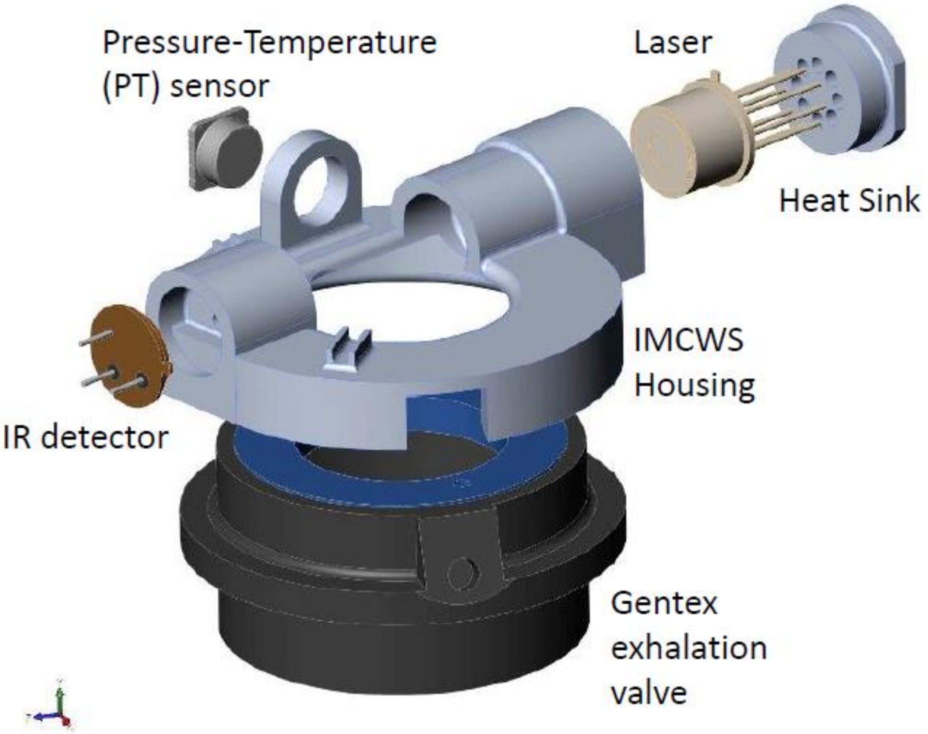


Figure 3 Exploded View Showing the Configuration of the Main Components

JPL In-Mask CO_2 & Water Sensor (IMCWS)
Memo To Address Technical Risk Issues Related to Mask Modifications
Prepared by John Graf (JSC) and Lance Christensen (JPL)
3/2/20

This memo is written to address one of the Technical Review Items identified as part of the AFRC Tech Brief Assessment of flight testing the JPL In-Mask CO_2 & Water Sensor (IMCWS) as part of the Pilot Breathing Assessment. This memo documents the modifications made to the mask, and it documents the reasons why the modifications to the mask will not affect mask function, performance, or structural integrity. The modifications to the mask are: 1) a connector is added to the mask, and 2) internal components with a total weight of less than 35 grams.

The risk issue of leakage through the mask around the connector is addressed by:

> The location, mounting technique, and connector type is part of the Gentex mask design – Gentex manufactures masks that have Glenair connectors in this location.
>
> The mask is fit check, and tested for leaks after manufacture.

The risk issue of leakage around the mask seal, by weighting down the mask is addressed by:

> The weight of the internal components inside the mask is less than 35 grams.
>
> The forces on the mask caused by the internal components are substantially less than the forces on the mask caused by the addition of the exhalation hose. The exhalation hose has been used successfully for all Pilot Breathing Assessment (PBA) flights using the VigilOX exhalation sensor block (ESB).
>
> Leakage forces caused by IMCWS are substantially less than leakage forces caused by the exhalation hose. Photos of the relevant components are shown in Figures 4, 5, and 6.

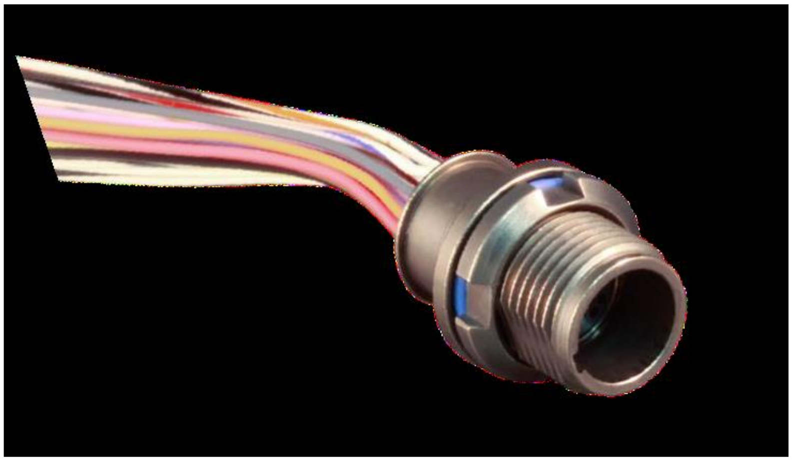


Figure 4 Glenair panel mount connector 880-004RB-K19M-M020J5-12

Figure 5 Glenair plug 880-001PA-K19M-M020J5-48

Figure 6 Photo of Gentex Mask with Glenair Connector

Memo

To Address Concerns About Oxygen Compatibility and Fire Safety for JPL Mask Sensor Components Being Involved in a Fire Triggered by a Spark of Static Electricity

John Graf, NASA JSC
March 12, 2020

Description of Hazard:

The mask environment includes elevated O_2 and new components are added to the mask. If the new components are susceptible to fire ignition from electrostatic discharge or overheating of an electrically energized component – there is a chance that a spark of static electricity could trigger a severe O_2 fire on the pilot's face.

Summary Description of Hazard Control:

The materials inside the mask can burn in extreme conditions, but they are hard to ignite in the environmental conditions of the mask (>1.1 atm/>50 °C/100% O_2). There are no credible ignition mechanisms capable of initiating a fire. The lack of ignition mechanism is the primary control of this hazard. Note: the laser/detector system used in the IMCWS if flight qualified for Crit 1 use – as part of the Laser Air Monitor (LAM).

Review of Ignition Mechanisms:

O_2 compatibility assessments survey and assess a set of ignition mechanisms that include:

- Particle Impact
- Heat of Compression
- Flow Friction
- Mechanical Impact
- Friction
- Fresh Metal Exposure
- Static Discharge
- Electrical Arc/Short
- Chemical Reaction
- Thermal Runaway
- Resonance
- External Heating

An assessment of each of these mechanisms is provided below:

Particle Impact	There are no high velocity gases that contain particulate
Heat of compression pressure	There are no compressed gases and no increase of gas
Flow friction	Gas velocities are low
Mechanical Impact	There are no large-scale mechanical forces
Friction	There are no moving parts with significant friction
Fresh metal exposure	There is no fresh metal
Static Discharge	Insufficient static energy – see analysis below
Electrical Arc/Short	Insufficient electrical power – see analysis below
Chemical Reaction	No reactive chemicals
Thermal Runaway	No porous materials, no chemical reactions

- Resonance	No acoustic oscillations
- External Heating	No external heating, environmental temperatures are low

Static Discharge:

The NASA White Sands Test Facility conducted a set of tests to determine the susceptibility of materials to ignition by static discharge. One set of tests were performed at 23.5 psi and 100% O_2. A fine wire (54 AWG) was placed next to highly flammable materials, including a 100% cotton t-shirt, and moleskin. With a fixed voltage of 22.5 V, current levels were increased until ignition was achieved, or the limits of the test facility were reached. Cotton t-shirt material did not ignite even when maximum power settings were used (8.1 W). Moleskin did not ignite, even with maximum power settings were used (6.8 W). These power settings are an order of magnitude higher than the power of commonly occurring electrostatic discharge (ESD) pulses. There is not enough energy in a spark of static electricity to ignite moleskin or cotton t-shirt material. The materials used in the JPL sensor are harder to ignite than either moleskin or cotton t-shirt material. Static discharge is not a credible ignition mechanism.

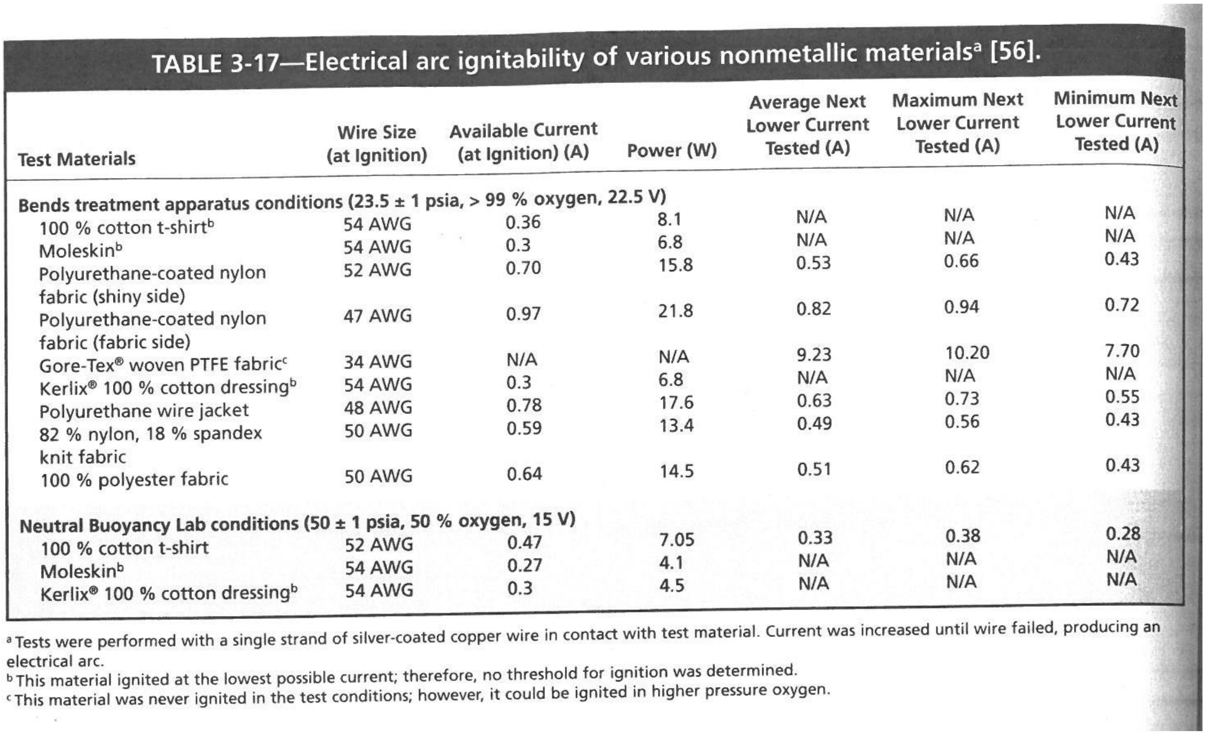


TABLE 3-17—Electrical arc ignitability of various nonmetallic materials[a] [56].

Test Materials	Wire Size (at Ignition)	Available Current (at Ignition) (A)	Power (W)	Average Next Lower Current Tested (A)	Maximum Next Lower Current Tested (A)	Minimum Next Lower Current Tested (A)
Bends treatment apparatus conditions (23.5 ± 1 psia, > 99 % oxygen, 22.5 V)						
100 % cotton t-shirt[b]	54 AWG	0.36	8.1	N/A	N/A	N/A
Moleskin[b]	54 AWG	0.3	6.8	N/A	N/A	N/A
Polyurethane-coated nylon fabric (shiny side)	52 AWG	0.70	15.8	0.53	0.66	0.43
Polyurethane-coated nylon fabric (fabric side)	47 AWG	0.97	21.8	0.82	0.94	0.72
Gore-Tex® woven PTFE fabric[c]	34 AWG	N/A	N/A	9.23	10.20	7.70
Kerlix® 100 % cotton dressing[b]	54 AWG	0.3	6.8	N/A	N/A	N/A
Polyurethane wire jacket	48 AWG	0.78	17.6	0.63	0.73	0.55
82 % nylon, 18 % spandex knit fabric	50 AWG	0.59	13.4	0.49	0.56	0.43
100 % polyester fabric	50 AWG	0.64	14.5	0.51	0.62	0.43
Neutral Buoyancy Lab conditions (50 ± 1 psia, 50 % oxygen, 15 V)						
100 % cotton t-shirt	52 AWG	0.47	7.05	0.33	0.38	0.28
Moleskin[b]	54 AWG	0.27	4.1	N/A	N/A	N/A
Kerlix® 100 % cotton dressing[b]	54 AWG	0.3	4.5	N/A	N/A	N/A

[a] Tests were performed with a single strand of silver-coated copper wire in contact with test material. Current was increased until wire failed, producing an electrical arc.

[b] This material ignited at the lowest possible current; therefore, no threshold for ignition was determined.

[c] This material was never ignited in the test conditions; however, it could be ignited in higher pressure oxygen.

From Safe Use of Oxygen and Oxygen Systems: ASTM MNL36. Second Edition, 2007

Electrical Arc/Short or External Heating of Materials to their Auto Ignition Temperature:

Materials can auto-ignite, if they are heated to a sufficient temperature. This analysis considers the highest temperature of the materials and compares them to autoignition temperatures. A thermal analysis of energized components concluded that the maximum temperature of any exposed surface of any material in the JPL sensor (inside the mask) is 50 °C. The power use is small, and the device is designed to wick heat away from energized components. The lowest rated operating temperature is 400 °C (the rated temperature for Kapton thin film). For the purposes of this analysis – the autoignition temperature of gasoline is 247 °C. If components were accidently soaked in gasoline – it would be unsafe to expose the materials to 247 °C temperature conditions. Maximum temperature of the JPL sensor materials is 50 °C – well below air intake temperature (AIT) (even if the materials were contaminated with hydrocarbons. There is too little electrical power to heat JPL sensor components to autoignition temperature.

Appendix 6: Standardization of Test Flights

Profile H

As a deliverable from this project, the Pilot Breathing Assessment (PBA) team developed a "Breathing System Functional Check Flight" profile, called **H**ealth check, comprised mainly of maneuvers from the other five flight profiles, and designated Profile H. The intent is to offer this profile to the flight test community as the first draft of a standard profile, which can be used to confirm proper functioning after a 'problem jet' has been fixed, to accept a jet out of depot-level maintenance, and to test a new or upgraded breathing system. The pilot must be equipped with a VigilOX or equivalent data system to record the required parameters.

The profile consists of a short Ground Block before and after the flying portion. The in-flight profile was designed with three major climbs and descents of varying speeds as large changes in altitude stress the cabin pressurization system as well as the breathing system and pilot. The profile is designed to be executed in the order it is written, without deviation if possible, so that the data can be compared to earlier check flights of the same aircraft or to any fleet data available.

While designed for the F-18, it should be easy to adapt to other fighter aircraft. The maneuvers and profile should be easily learned by any Functional Check Flight (FCF)-qualified pilot. The profile requires working airspace from 5,000 ft pressure altitude (PA) up to 30,000 ft PA and could be accomplished in airspace with as little as 30 nm between boundaries, though an area allowing longer runs would be more efficient. In the F-18, Profile H can be accomplished in a single sortie in both single-seat and two-seat aircraft equipped with a centerline fuel tank, if the working airspace is nearby. If there is a longer transit to the airspace, wing tanks would likely be necessary.

Profile H: Detailed Procedures

Pre-Step:

Approximately 1 hour prior to takeoff, conduct RAD-97 capnography and Spirometry measurements seated in a briefing room without flight gear.

Ground Ops:

Strap in normally to the cockpit, but before donning helmet, conduct RAD-97 capnography and Spirometry. Don helmet and power on the exhalation sensor block (ESB) and inhalation sensor block (ISB). Don the mask and Event Mark. Leave the mask up until after engine shutdown, except when specified on a test card. Conduct normal engine start and checklist through Before Taxi, ensuring aircraft bus data recorder is powered on.

Card 1: Ground Block 1

A. Baseline Breathing [ON/NORM/NORM (USAF) / ON (Navy)]: Accomplish this card with the canopy UP.

A1. Event Mark and breath normally for 3 minutes, noting any abnormalities with the mask valves or regulator.

A2. Event Mark and lower the mask, breathing normally for 2 minutes.

A3. Raise the mask, conduct an Event Mark, and ensure a good seal. Perform a PRICE check (USAF only). Breathe normally for 1 minute.

A4. Event Mark and take 3 breaths with Maximum Inhalation and Normal Exhalation (fill your lungs as if getting ready to blow up a balloon, but then relax and let the air flow out normally). Wait 30 seconds before the next step.

A5. Event Mark and take 3 breaths with Maximum Inhalation and Maximum Exhalation (fill your lungs quickly and completely as if getting ready to blow up a balloon and then exhale forcibly as if trying to blow out a small fire). Note anything that affects the work of breathing during these exercises.

B. Taxi: If outside air temperature permits, close the canopy and Event Mark. If necessary, for cockpit cooling, it is acceptable to delay lowering the canopy until just prior to takeoff.

Card 2: Takeoff & Mil Power Climb

A. Mil Power Takeoff: If the canopy is still up, lower the canopy and Event Mark before calling for takeoff clearance.

A1. Taking Runway: Event Mark while taxiing onto the runway, shortly before beginning takeoff roll. Perform a normal takeoff using Military power.

A2. Weight-off-wheels: Note as accurately as possible the weight-off-wheels time.

B. Set Altimeter – 29.92: As soon as possible, in accordance with local procedures, set the altimeter to 29.92.

C. Mil Power Climb: Level off at 5,000 ft PA and stabilize at 350 knots calibrated airspeed (KCAS). When ready to begin climb, Event Mark and select MIL power while initiating a moderate pull to hold 350 KCAS. The initial flight path angle will be approximately 12 degrees, depending on weight and configuration. Roll inverted and pull the nose down to level off at 15,000 ft PA.

Card 3: 15K Level Systems Operations

A. 15,000 Pressure Altitude Baseline: Conduct the following exercises at 15,000 ft PA and 250 KCAS in level flight; maintain a constant airspeed. If necessary to turn for airspace or traffic, do so between exercises. Do not talk unless required for Air Traffic Control (ATC) communications or crew coordination.

A1. Event Mark and breathe normally for 3 minutes.

A2. Event Mark and take 3 breaths with Maximum Inhalation and Normal Exhalation (fill your lungs as if getting ready to blow up a balloon, but then relax and let the air flow out normally). Wait 30 seconds.

A3. Event Mark and take 3 breaths with Maximum Inhalation and Maximum Exhalation (fill your lungs quickly and completely as if getting ready to blow up a balloon and then exhale forcibly as if trying to blow out a small fire).

Note anything that affects the work of breathing during these exercises.

Card 4: Mask-On / Mask-Off Comparison

A. 15,000 Breathing Comparison: Conduct the following exercises at 15,000 ft PA and 250 KCAS in level flight; maintain a constant airspeed. If necessary to turn for airspace or traffic, do so between exercises. Do not talk unless required for ATC communications or crew coordination.

A1. Time how long it takes for 10 Normal Breaths. Do not attempt to regulate your breathing, just relax and breathe naturally.

A2. Verify that the Cabin Altitude is within limits at approximately 8,000’ before the next step.

A3. Event Mark and remove the mask.

A4. Time how long it takes for 10 Normal Breaths. Do not attempt to regulate your breathing, just relax and breathe naturally.

A5. Event Mark and then don the mask, ensure a proper seal, and breathe normally for 1 minute.

Card 5: 15K Talking Script

A. 15,000 Talking Script: Set up so the entire script can be read without having to turn the aircraft for airspace. Stabilize at approximately 15,000 ft PA and 250 KCAS for the entire card. Event Mark and give a description over the intercom of the current mission in complete sentences, following the prompts on the card. Speak in a normal cadence as if carrying on a conversation. Give the following information:

Name

Flight Profile

Date

Altitude

Airspeed

Heading

Cabin Pressure

Card Number

Any notable breathing-related events

Card 6: Mil Power Climb

A. Mil Power Climb: Start level at 15,000 ft PA and stabilize at 350 KCAS. When ready to begin climb, Event Mark and select MIL power while initiating a moderate pull to hold 350 KCAS. The initial flight path angle will be approximately 10 degrees, depending on weight and configuration. When 350 KCAS equals 0.85 Mach, hold the Mach constant. Roll inverted and pull the nose down to level off at 30,000 ft PA.

Card 7: OBOGS Descent

A. OBOGS Descent:

A1: Start at 30,000 ft PA and 250 KCAS. Event Mark and smoothly select IDLE power while initiating a descent to hold 250 KCAS. Attempt to set up this maneuver in the airspace so only small turns are required for traffic or weather; the descent will take approximately 30 nm.

A2. Level off at 7,000 ft PA and Event Mark. Wait 2 minutes before starting the next card.

Card 8: Mil Power Climb

A. Mil Power Climb: Start level at 7,000 ft PA and stabilize at 350 KCAS. When ready to begin climb, Event Mark and select MIL power while initiating a moderate pull to hold 350 KCAS. The initial flight path angle will be approximately 15 degrees, depending on weight and configuration. Roll inverted and pull the nose down to level off at 25,000 ft PA.

Card 9: 25K Level Systems Operations

A. 25K Pressure Altitude Baseline: Conduct the following exercises at 25,000 ft PA and 250 KCAS in level flight; maintain a constant airspeed. If necessary to turn for airspace or traffic, do so between exercises. Do not talk unless required for ATC communications or crew coordination.

A1. Event Mark and breathe normally for 3 minutes.

A2. Event Mark and take 3 breaths with Maximum Inhalation and Normal Exhalation (fill your lungs as if getting ready to blow up a balloon, but then relax and let the air flow out normally). Wait 30 seconds.

A3. Event Mark and take 3 breaths with Maximum Inhalation and Maximum Exhalation (fill your lungs quickly and completely as if getting ready to blow up a balloon and then exhale forcibly as if trying to blow out a small fire).

Note anything that affects the work of breathing during these exercises.

Card 10: Combat Descent and Zoom Climb

A. Combat Descent: Start at 25,000 ft PA and 0.85 Mach. Event Mark and slowly pull the power to IDLE while lowering the nose to maintain 0.85 Mach. Continue lowering the nose while extending the speed brake to maintain 0.85 Mach. The flight path angle will be approximately 30 degrees down. When 0.85 Mach equals 420 KCAS, maintain 420 KCAS. Initiate dive recovery at 8,000 ft PA using 2 to 3 g and MIL Power. Immediately transition to the zoom climb in the next step.

B. Zoom Climb: Continue 2- to 3 g MIL Power pull to achieve a climb at a 30-degree flight path angle, wait a few seconds and select IDLE Power. Roll inverted and pull the nose down to level off at 12,000 ft PA and 250 KCAS.

C. Normal Breathing: Event Mark and breathe normally for 1 minute in level flight at approximately 12,000 ft PA and 250 KCAS.

Card 11: Level Accel/Decel

A. Level Accel: Start at 12,000 ft PA and 250 KCAS. Event Mark, select MIL Power, and accelerate in straight and level flight to 0.95 Mach. If the aircraft stops accelerating at less than 0.95 Mach, it is acceptable to consider the Accel complete.

B. Level Decel: Immediately upon reaching 0.95 Mach (or max Mach), Event Mark and select IDLE power to decelerate in straight and level flight.

C. End Decel: Event Mark upon decelerating to 250 KCAS.

Card 12: G-Exercise

A. G-Exercise:

A1: Set up at 12,000 ft PA and 400 KCAS. Event Mark and initiate a 3- to- 4-g turn in MIL power while maintaining altitude. Airspeed will bleed off. Roll out after 90 degrees of heading change.

A2: Set up at 15,000 ft PA and 450 KCAS. Event Mark and initiate a 4- to 5-g turn in MIL power while maintaining altitude. Airspeed will bleed off. Roll out after 90 degrees of heading change.

Card 13: High G Maneuvering

A. 5 g Constant Descending Turn: Set up at 15,000 ft PA and 480 KCAS. Event Mark, select MIL power, and roll into a 5-g turn with a -10-degree flight path angle (FPA). Hold the 5-g descending turn for a total of 1 min. Descend no lower than 7,000’ PA. At the 1-min mark, return quickly to 1-g, roll to wings level, and return to level flight. Wait 2 minutes before starting the next card. It is acceptable to slow to 250 KCAS to conserve fuel.

Card 14: Max AB Climb

A. MAX Power Climb: Start level at 7,000 ft PA and stabilize at 350 KCAS. When ready to begin climb, Event Mark and select MIL power while initiating a moderate pull to hold 350 KCAS. As the flight path angle passes approximately 15 degrees, select MAX power and continue to increase the flight path angle to maintain 350 KCAS. The initial flight path angle will be approximately 30 degrees, depending on weight and configuration. When 350 KCAS equals 0.85 Mach, hold the Mach constant. Roll inverted at approximately 28,500 ft and pull the nose down to level off at 30,000 ft PA.

Card 15: 30K Level Systems Operations

A. 30,000 Pressure Altitude Baseline: Conduct the following exercises at 30,000 ft PA and 250 KCAS in level flight; maintain a constant airspeed. If necessary to turn for airspace or traffic, do so between exercises. Do not talk unless required for ATC communications or crew coordination.

A1. Event Mark and breathe normally for 3 minutes.

A2. Event Mark and take 3 breaths with Maximum Inhalation and Normal Exhalation (fill your lungs as if getting ready to blow up a balloon, but then relax and let the air flow out normally). Wait 30 seconds.

A3. Event Mark and take 3 breaths with Maximum Inhalation and Maximum Exhalation (fill your lungs quickly and completely as if getting ready to blow up a balloon and then exhale forcibly as if trying to blow out a small fire).

Note anything that affects the work of breathing during these exercises.

Card 16: Cruise Descent

A. Cruise Descent:

A1: Select the DEFOG lever to HIGH.

A2: Start at 30,000 ft PA and 300 KCAS. Event Mark and smoothly select 80% power while initiating a descent to hold 300 KCAS. Attempt to set up this maneuver in the airspace so only small turns are required for traffic or weather; the descent will take approximately 20 nm.

A3. Level off at 20,000 ft PA and Event Mark. Wait 2 minutes before starting the next card.

A4: Select the DEFOG lever to NORM.

Card 17: Spiral Descent/Defensive BFM

A. Spiral Descent/Defensive Basic Fighter Maneuvering (BFM): This is a series of higher g pulls followed by lower g accels to regain airspeed, such as is encountered while conducting defensive BFM. Start at 20,000’ PA and 350 KCAS. Event Mark, then select MIL power and roll into a 4- to 5-g level turn. When the airspeed bleeds off to 300 KCAS, reduce pull to 2 g and descend at 5 to 10 degrees FPA to accelerate back to 350 KCAS. Reaching 350 KCAS, pull 4 to 5 g to bring the flight path back to the horizon and hold until reaching 300 KCAS. Continue alternating the level pull/decel and descending accel for a total of 3 minutes. Descend NLT 5000 ft PA/2000 ft above ground level (AGL).

B. Normal Breathing: Event Mark and breathe normally for 3 minutes in straight and level flight at the ending altitude from the previous step. Maintain a constant airspeed. If possible, avoid having to turn for airspace or traffic. Do not talk unless required for ATC communications or crew coordination.

Card 18: Return to Base (RTB)

A. Set local altimeter

B. Perform a normal landing to a full stop and note the time of weight-on-wheels. It is acceptable to conduct multiple patterns for training; note only the time of the full stop.

C. Event Mark after exiting the runway and accomplishing the After Landing checklist. Leave the canopy down for taxi unless required for cockpit cooling. Keep the mask up until after engine shutdown.

D. Taxi to parking.

Card 19: Ground Block II

A. Accomplish this card with the canopy DOWN.

B. Baseline breathing [ON/NORM/NORM (USAF) / ON (Navy)]

B1. As soon as stopped in parking, Event Mark and breathe normally for 3 minutes.

B2. Event Mark and take 3 breaths with Maximum Inhalation and Normal Exhalation (fill your lungs as if getting ready to blow up a balloon, but then relax and let the air flow out normally). Wait 30 seconds before the next step.

B3. Event Mark and take 3 breaths with Maximum Inhalation and Maximum Exhalation (fill your lungs quickly and completely as if getting ready to blow up a balloon and then exhale forcibly as if trying to blow out a small fire). Note anything that affects the work of breathing during these exercises.

Shutdown:

A. Event Mark and raise the canopy.

B. Accomplish normal shutdown procedures.

C. Event Mark, lower the mask, and remove helmet.

D. Conduct Post-flight Rad-97 capnography and Spirometry while still fully strapped into the seat.

Postflight:

Approximately 1 hour after shutdown, conduct RAD-97 capnography and Spirometry measurements seated in a briefing room without flight gear.

Appendix 7: F-35 Pilot Interviews and Ground Test Data

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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).

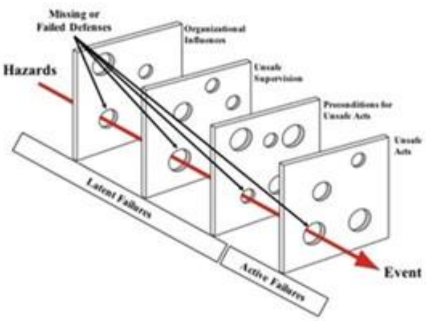

Figure 2.1. The Swiss Cheese Model of Accident Causation (adapted from Reason, 1990)

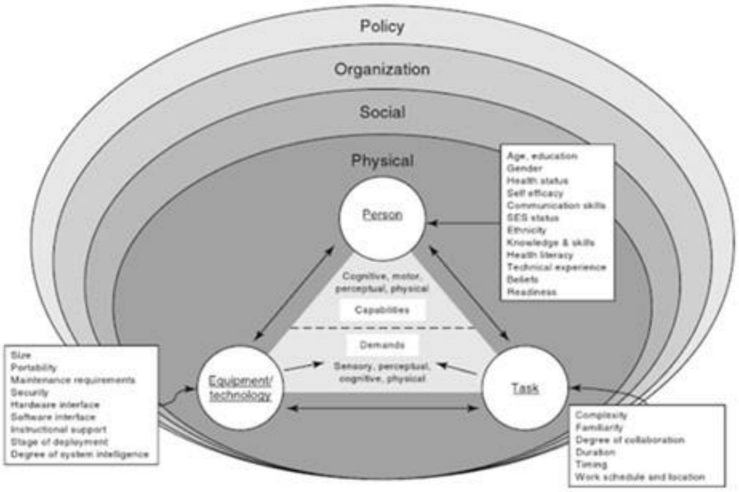

Figure 2.2. Human Factors Model of Person-Task-Equipment System (Czaja & Nair, 2012)

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.

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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.

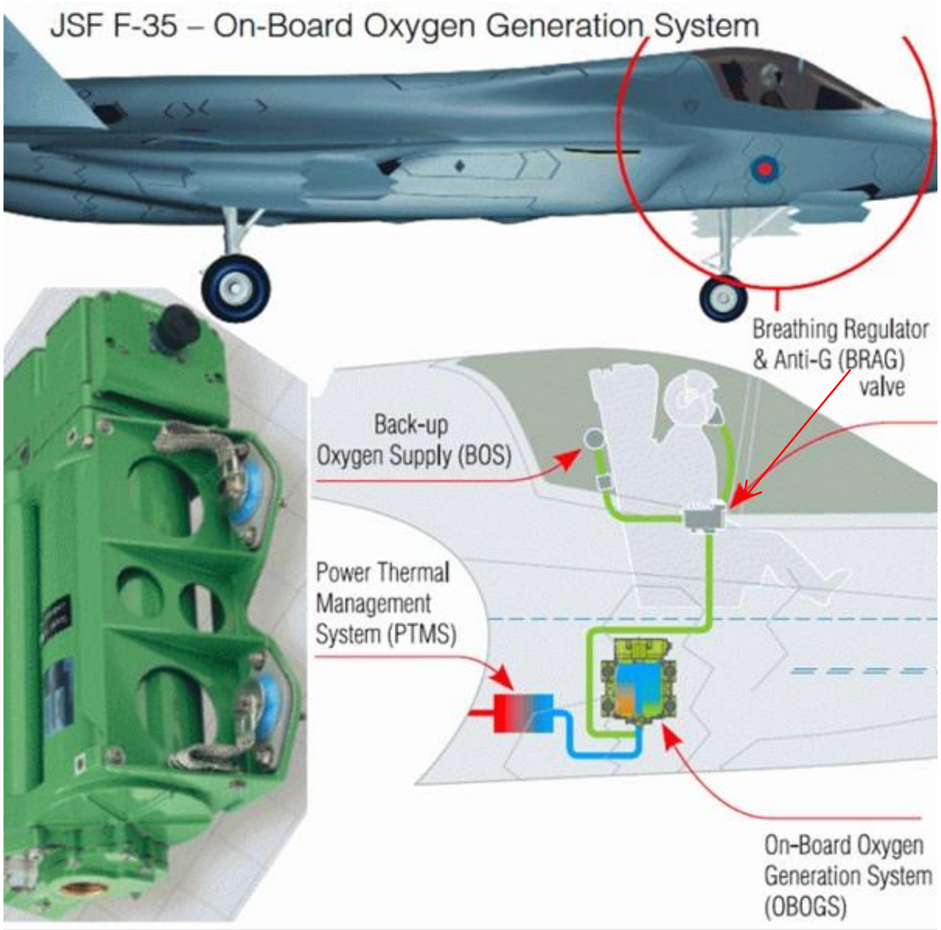


Figure 4.2. General Layout for F-35 Life Support System (Image from Google)

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

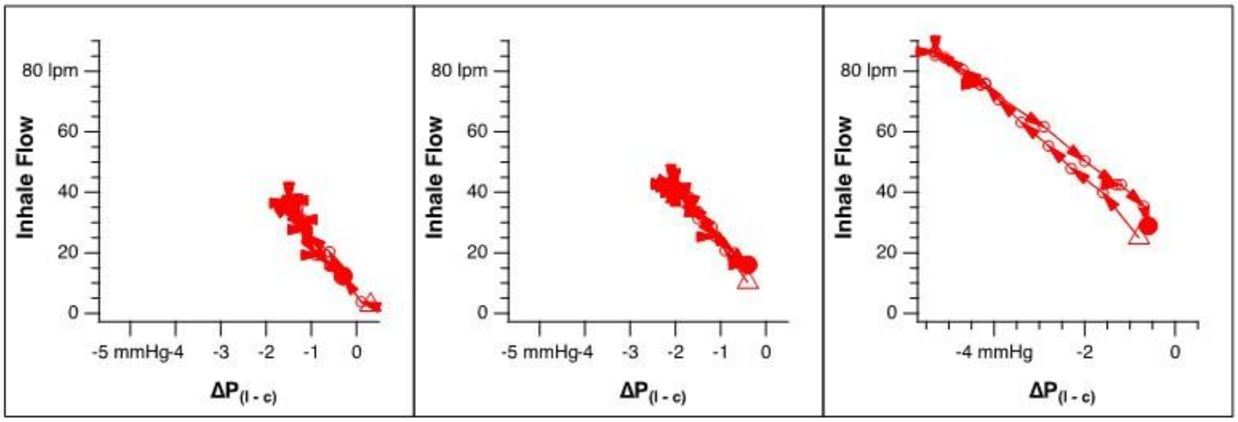


Figure 5.1. Inhale Flow vs Regulator Outlet Differential Pressure for a NASA F-18 with diluter demand regulator; showing nominal hysteresis. Note the linear relationship between flow and demand pressure over time.

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

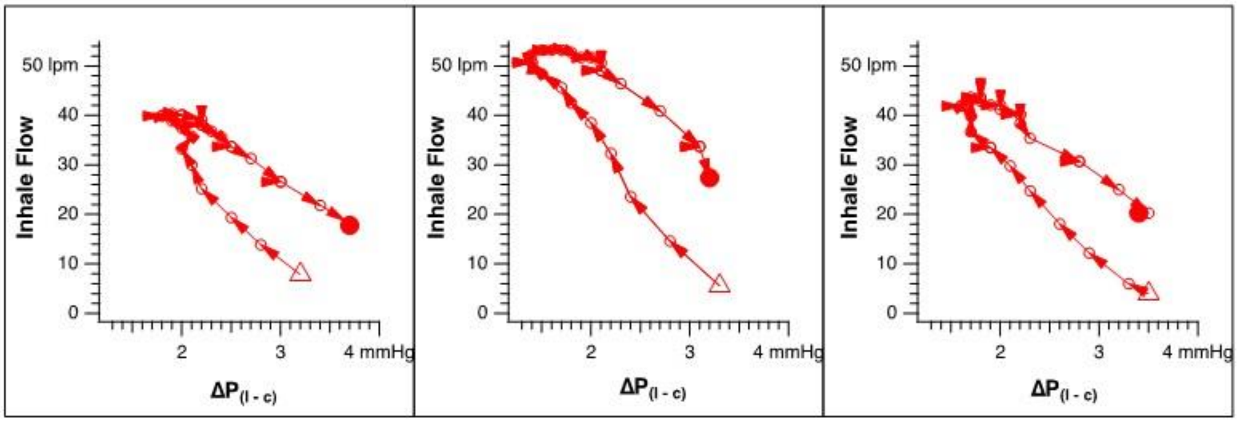


Figure 5.2. Inhale flow as a function of line-cabin differential pressure for NASA F-18 with Safety Pressure Regulator; showing pressure and flow hysteresis, with flow lagging behind pressure early. Later in the breath, flow exceeds demand.

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

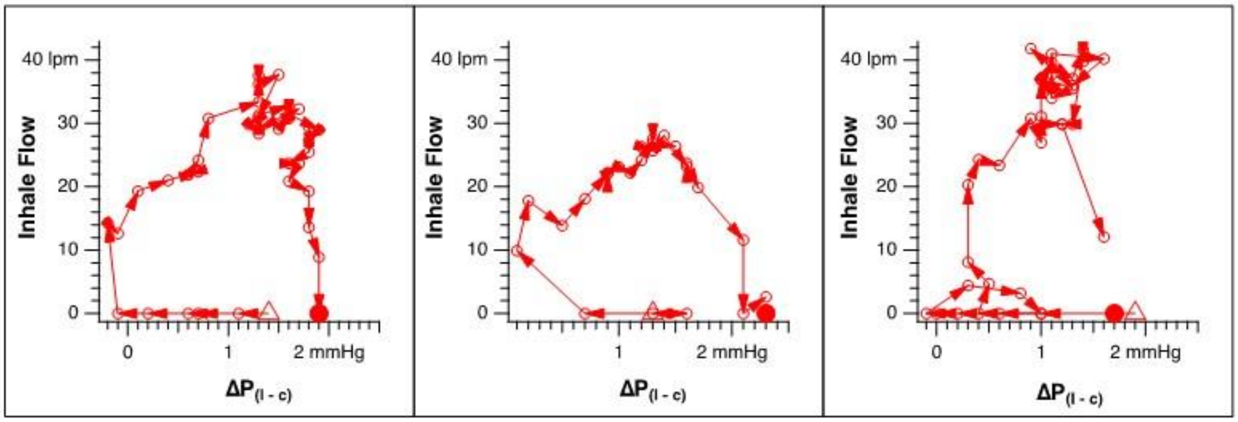


Figure 5.3. Breathing Pressure vs Inhale flow for F-35 aircraft, demonstrating severely non-linear path with extreme hysteresis and large amounts of deviation.
Early in a breath, there is no flow despite increasing demand. In the middle of the breath, flow is complex and overshoots demand. At the end of the breath, pressure remains high as demand drops.

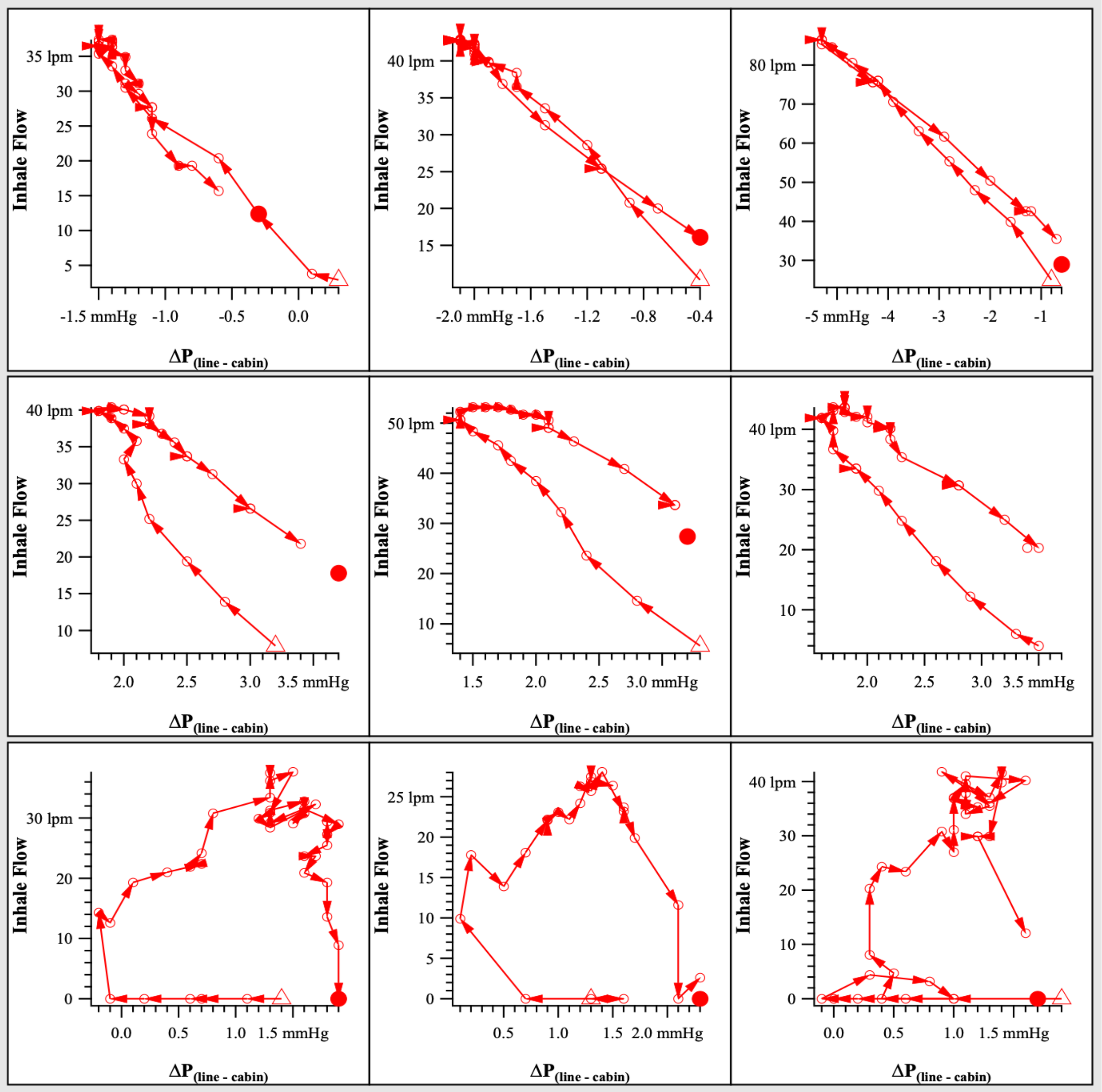


Figure 5.4. Comparison of hysteresis: (top) F-18 with diluter demand regulator (middle) F-18 with demand only and safety pressure (bottom) F-35 with demand only and safety pressure (figures rescaled to focus on hysteresis effect)

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.

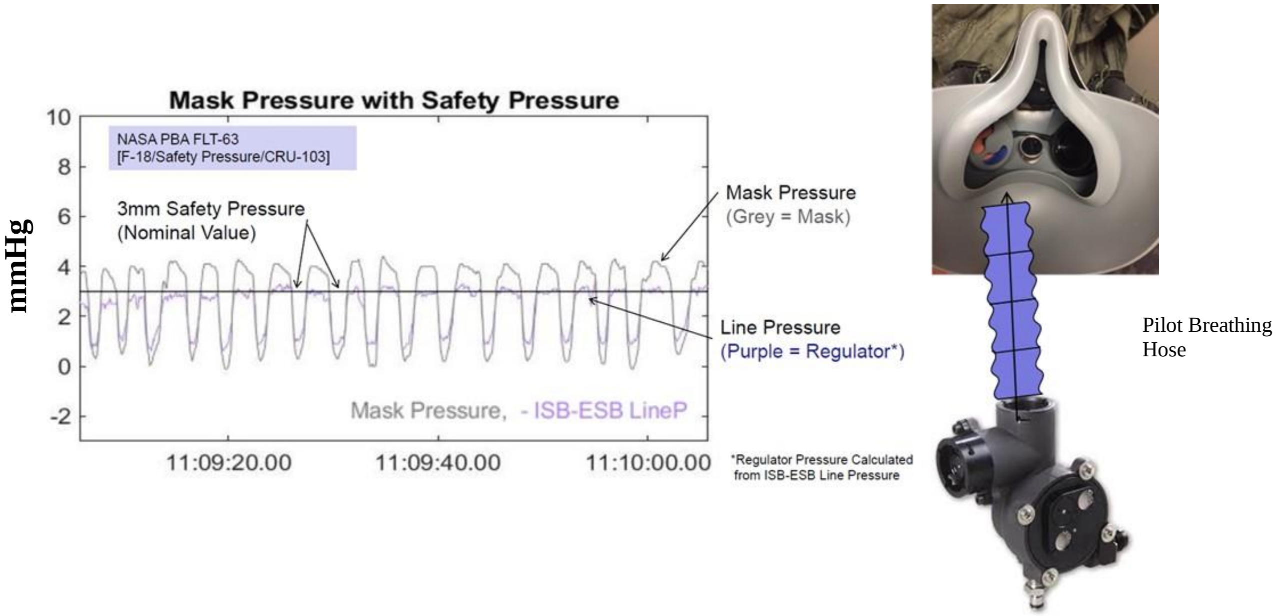


Figure 5.5. Ground data from a NASA F-18 demonstrating nominal mask pressure vs line pressure interaction. A CRU-103 Regulator, Pilot Breathing Hose, and Mask are shown on the right.

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.

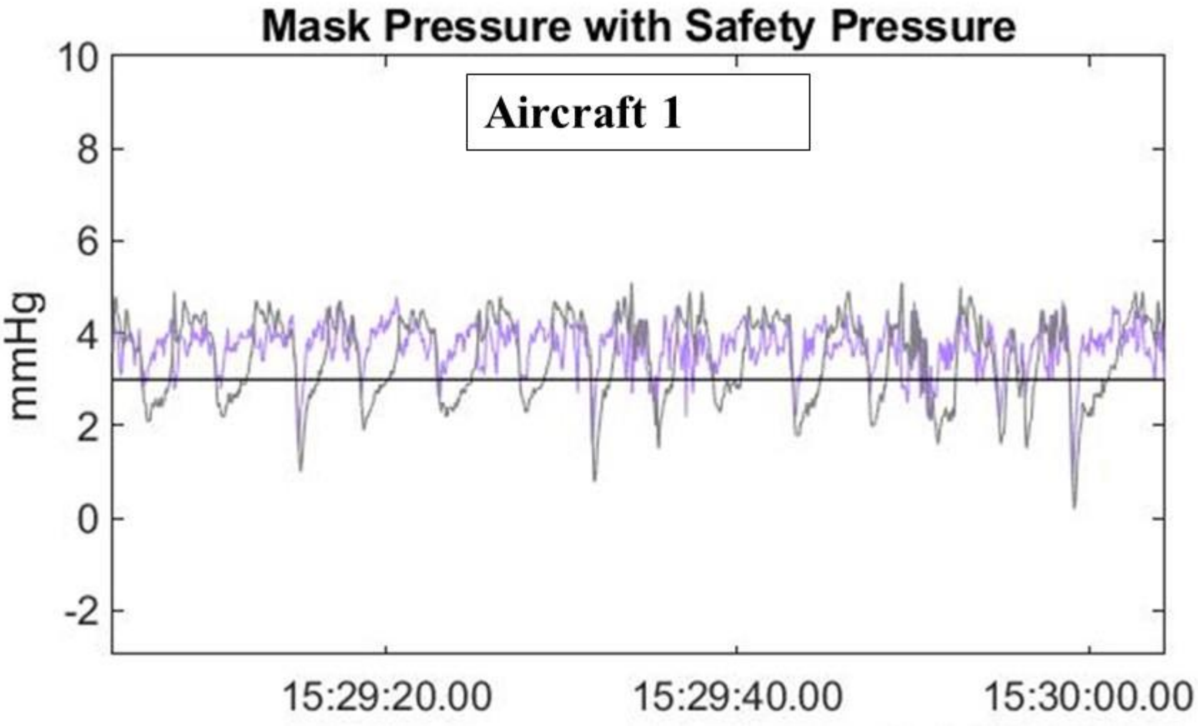


Figure 5.6. Mask Pressure (grey) vs Line Pressure (purple) from F-35 Aircraft 1

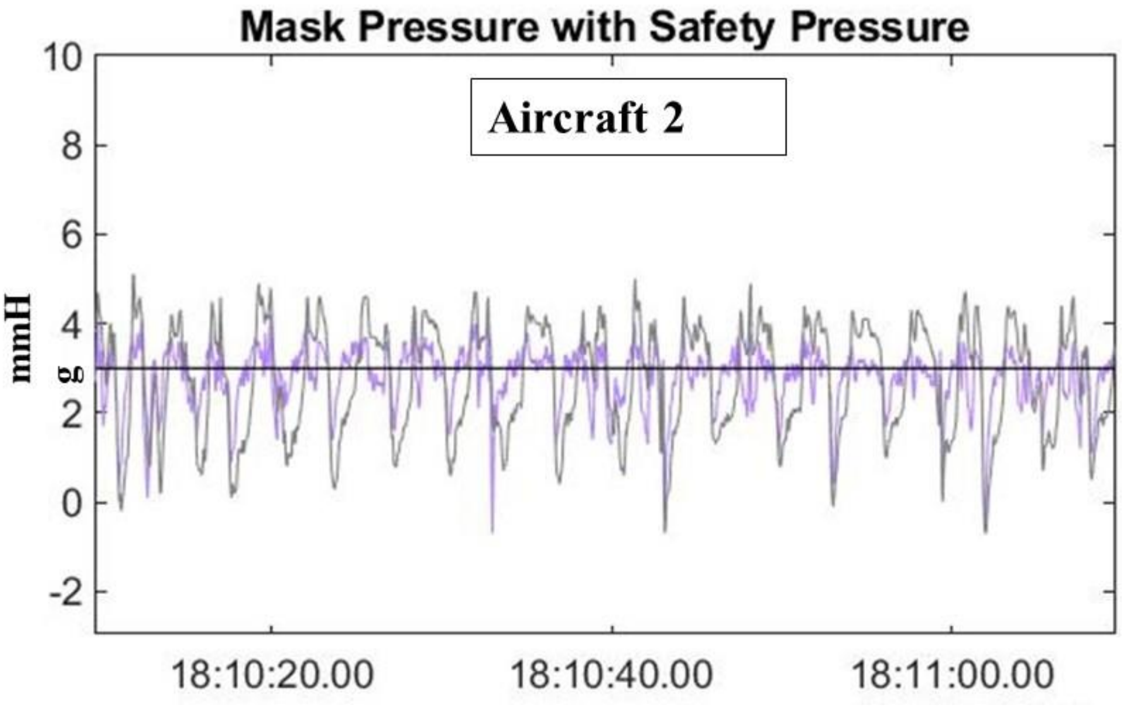


Figure 5.7. Mask Pressure (grey) vs Line Pressure (purple) from F-35 Aircraft 2

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.

Exhale Oscillations: 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.

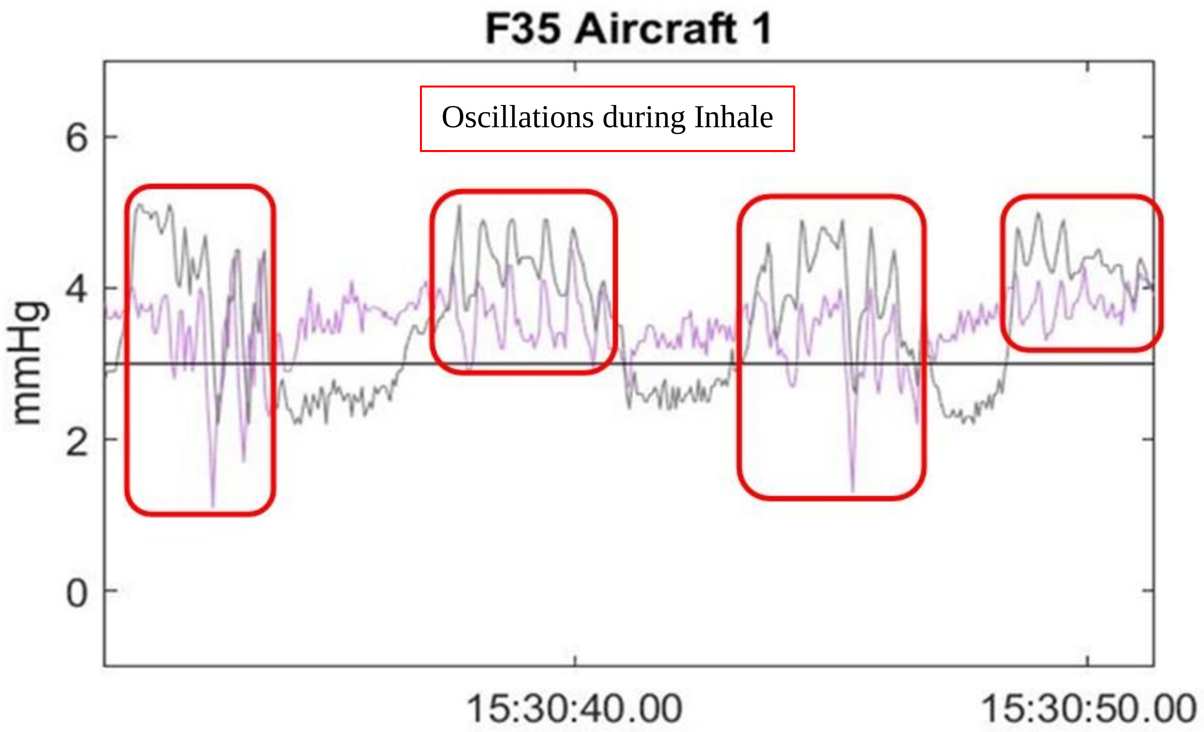


Figure 5.9. Close up view of oscillations showing mask pressure (grey) and line pressure (purple) on Aircraft 1.

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.

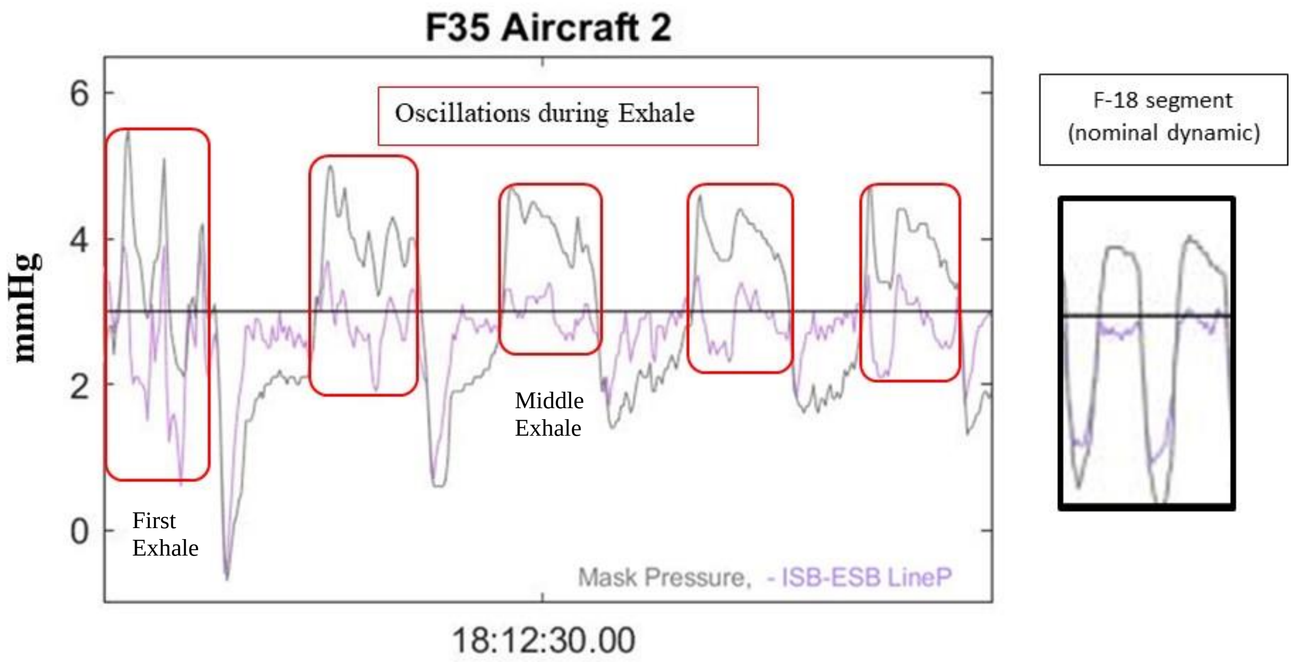


Figure 5.10. Close up view of oscillations showing mask pressure (grey) and line pressure (purple) on Aircraft 2.

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.

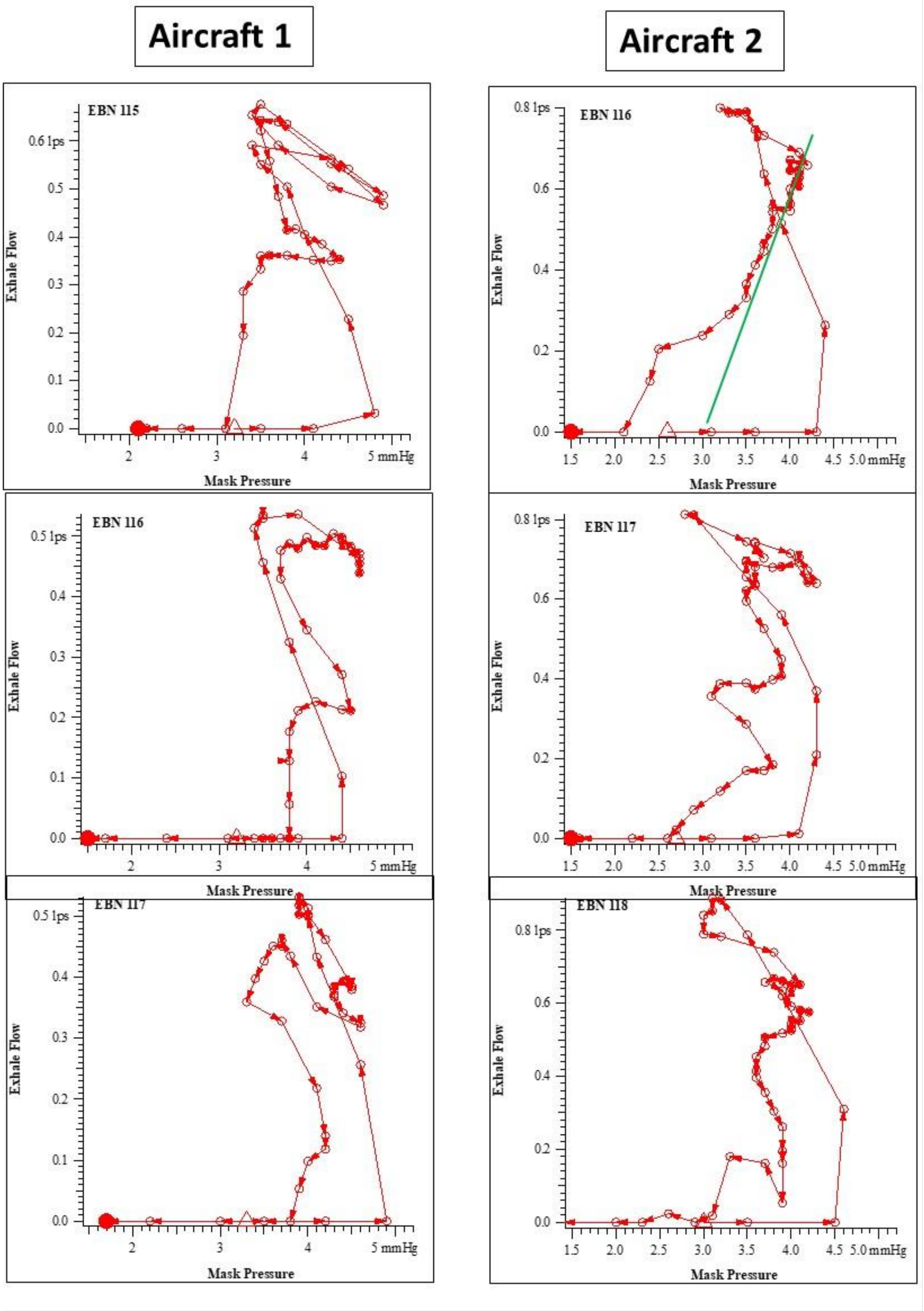


Figure 5.11. Exhale Flow versus Mask Pressure from Aircraft 1 and Aircraft 2.

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)

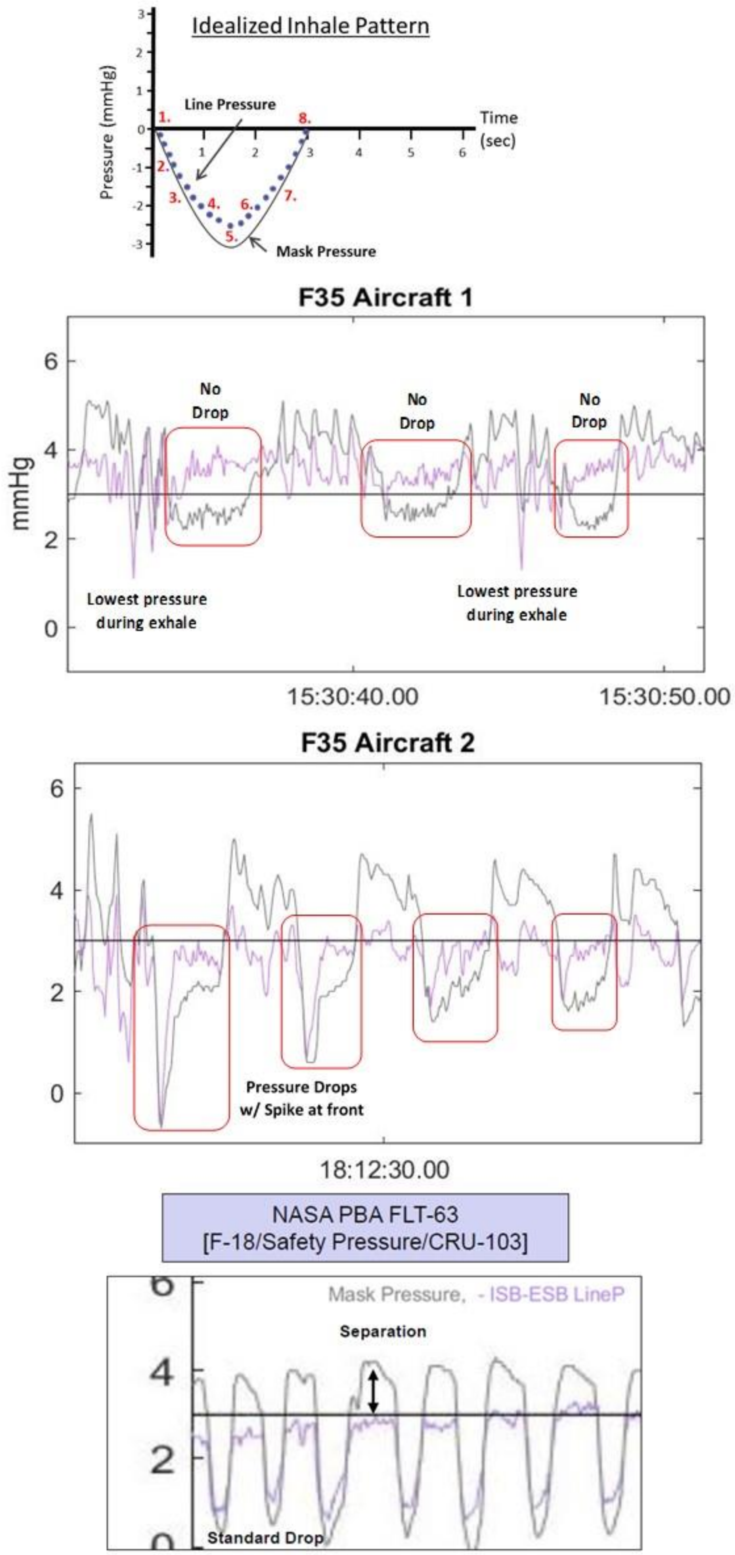


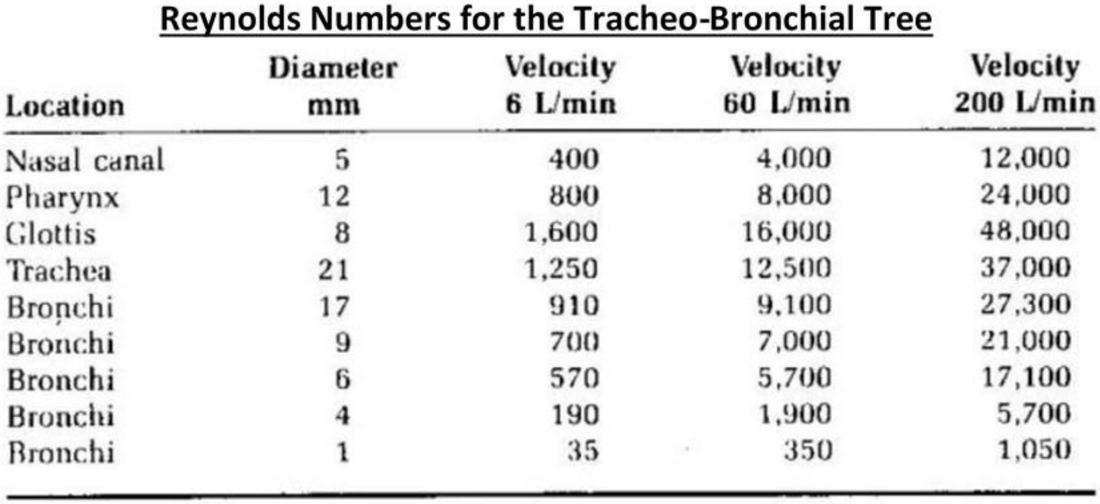
Figure 5.12. Mask Pressure vs Line Pressure Close up of inhale oscillations for F-35 Aircraft compared with nominal performance experienced in F-18.

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.

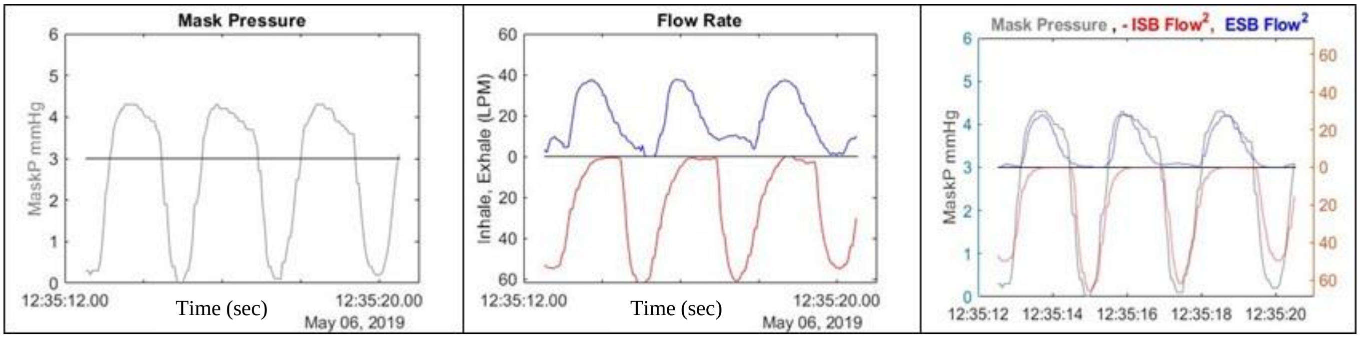


Figure 5.14. Mask Pressure (left), resulting Flow Rate (middle), and correlation when superimposed (right), shown using an F-18 sample. This is in direct conflict with observed F-35 behavior.

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).

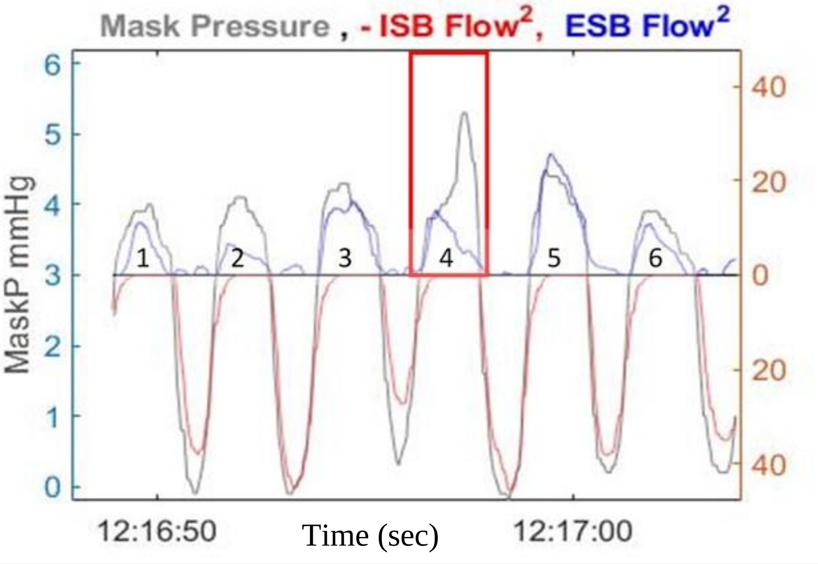


Figure 5.15. Exhale Breath #4 flow peaks at start of exhale. Mask pressure peaks at the end, as flow trends down. Shown using an F-18 sample. Breath #4 is an infrequently anomaly.

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)

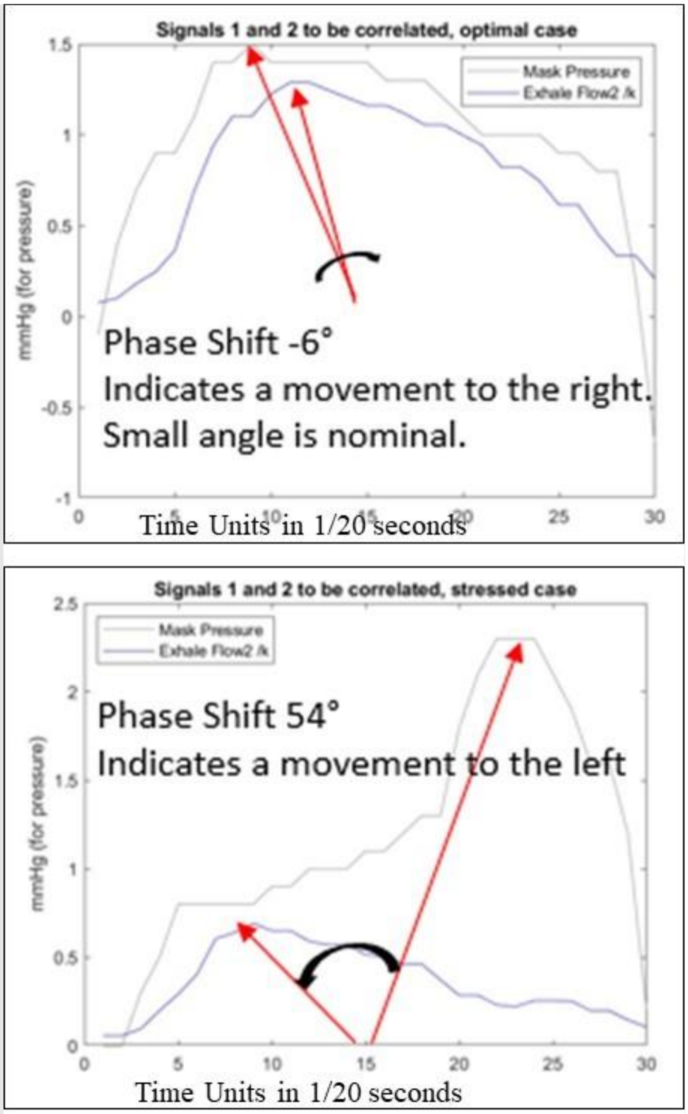


Figure 5.16. Exhale Breath #5 (top) and Exhale Breath #4(bottom) zoomed in view of breaths from Figure 5.15, shown using an F-18 sample.

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.

Quantitative Results: 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.

Correlation Results: 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.

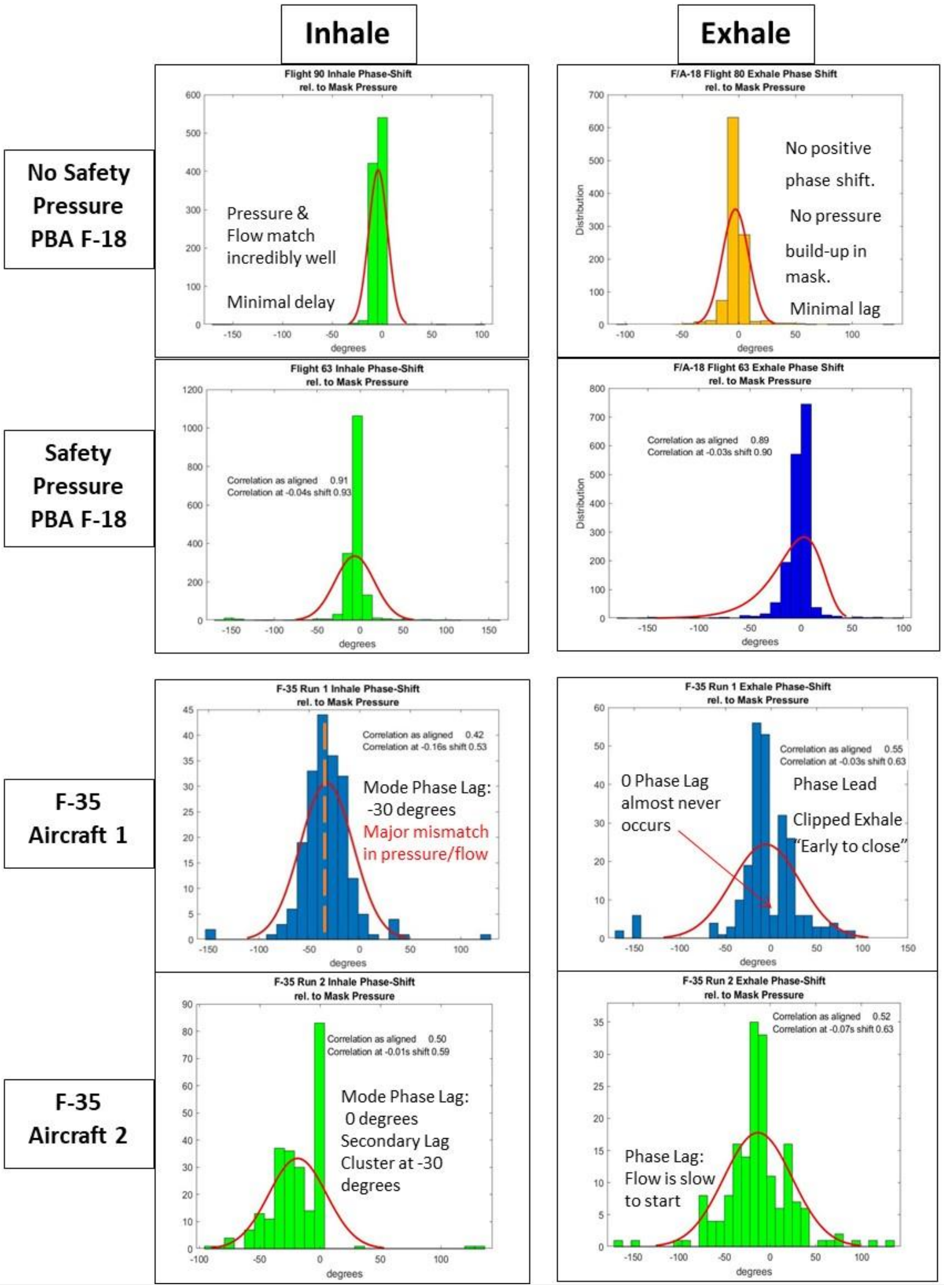


Figure 5.17. Phase Shift Plots of Inhale/Exhale for PBA F-18 and F-35 Aircraft 1 and 2.
F-35 aircraft exhibit increased phase shift and more erratic breathing behavior than legacy F-18 aircraft with or without safety pressure. In ideal breathing all flow should correlate to the driving pressure, and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

<u>A micro look at the F-35 Inhale</u>: 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.

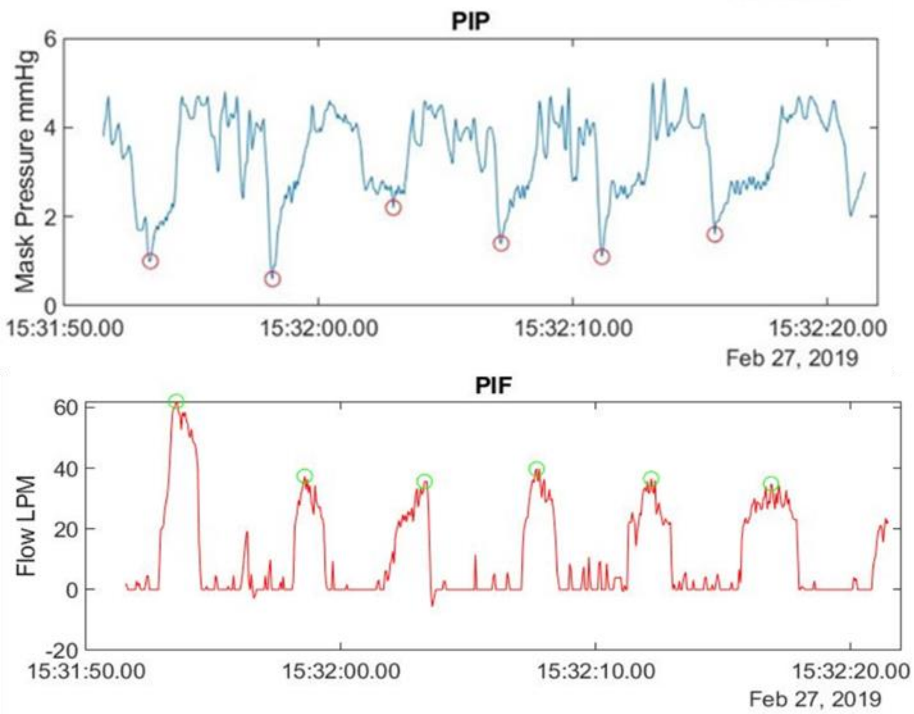


Figure 5.18. Sample F-35 Peak Inspiratory Pressure (PIP) and Peak Inspiratory Flow (PIF), where the flow should be much closer co-aligned as a response to the driving pressure

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.

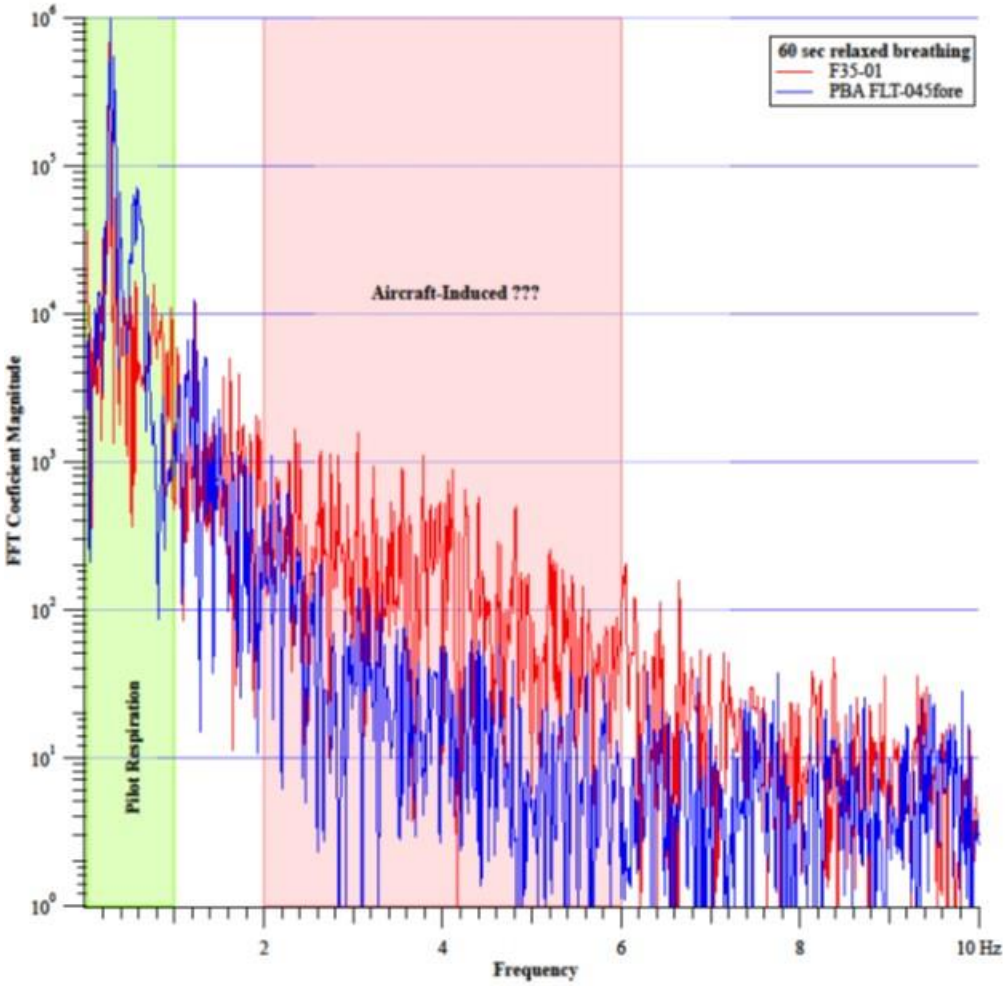


Figure 5.19. Fast Fourier Transform comparing F-18 to F-35 mask pressure frequency components demonstrating the increased power loading on the pilot breathing response in F-35.

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.

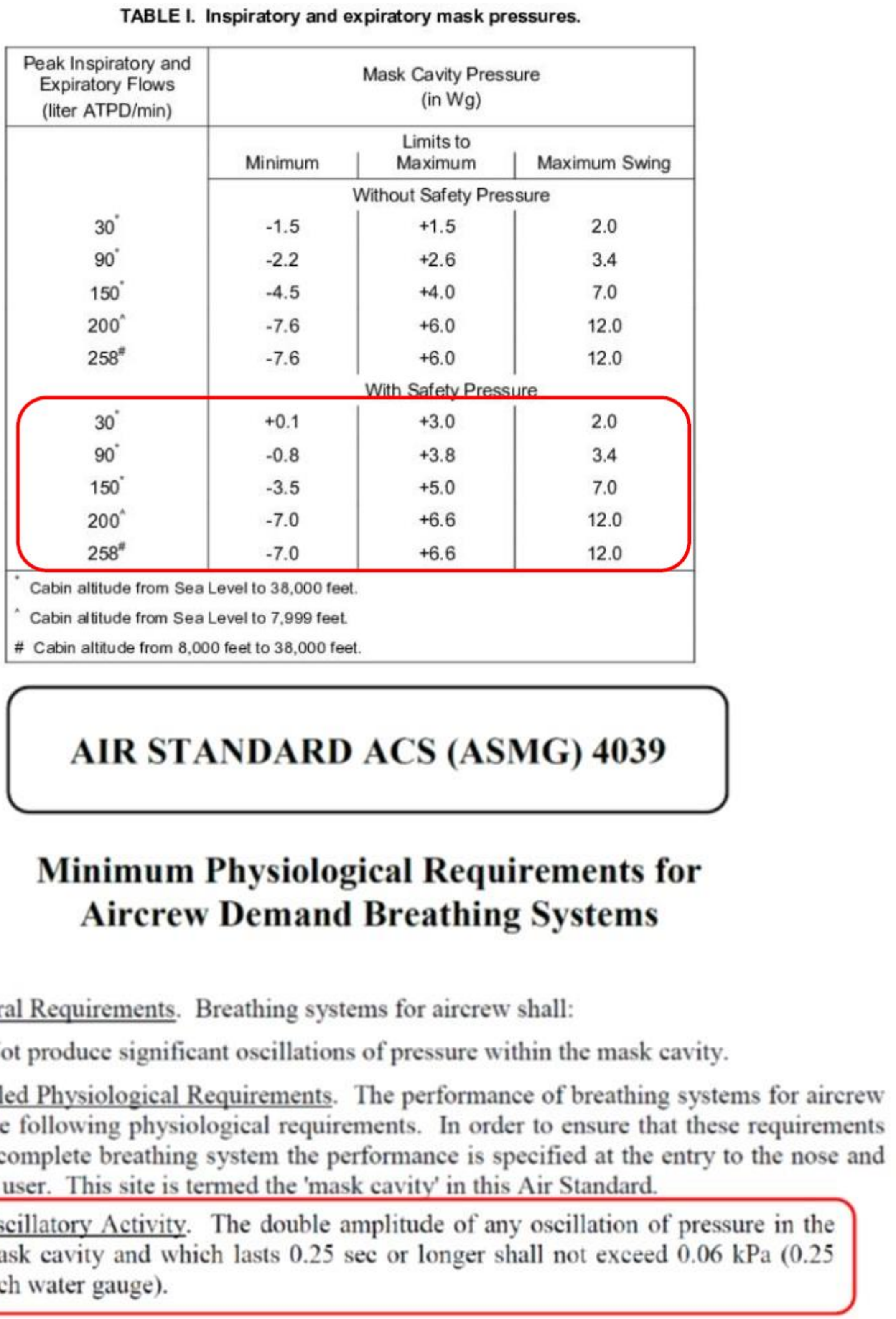


TABLE I. Inspiratory and expiratory mask pressures.

Peak Inspiratory and Expiratory Flows (liter ATPD/min)	Mask Cavity Pressure (in Wg)		
	Minimum	Limits to 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.

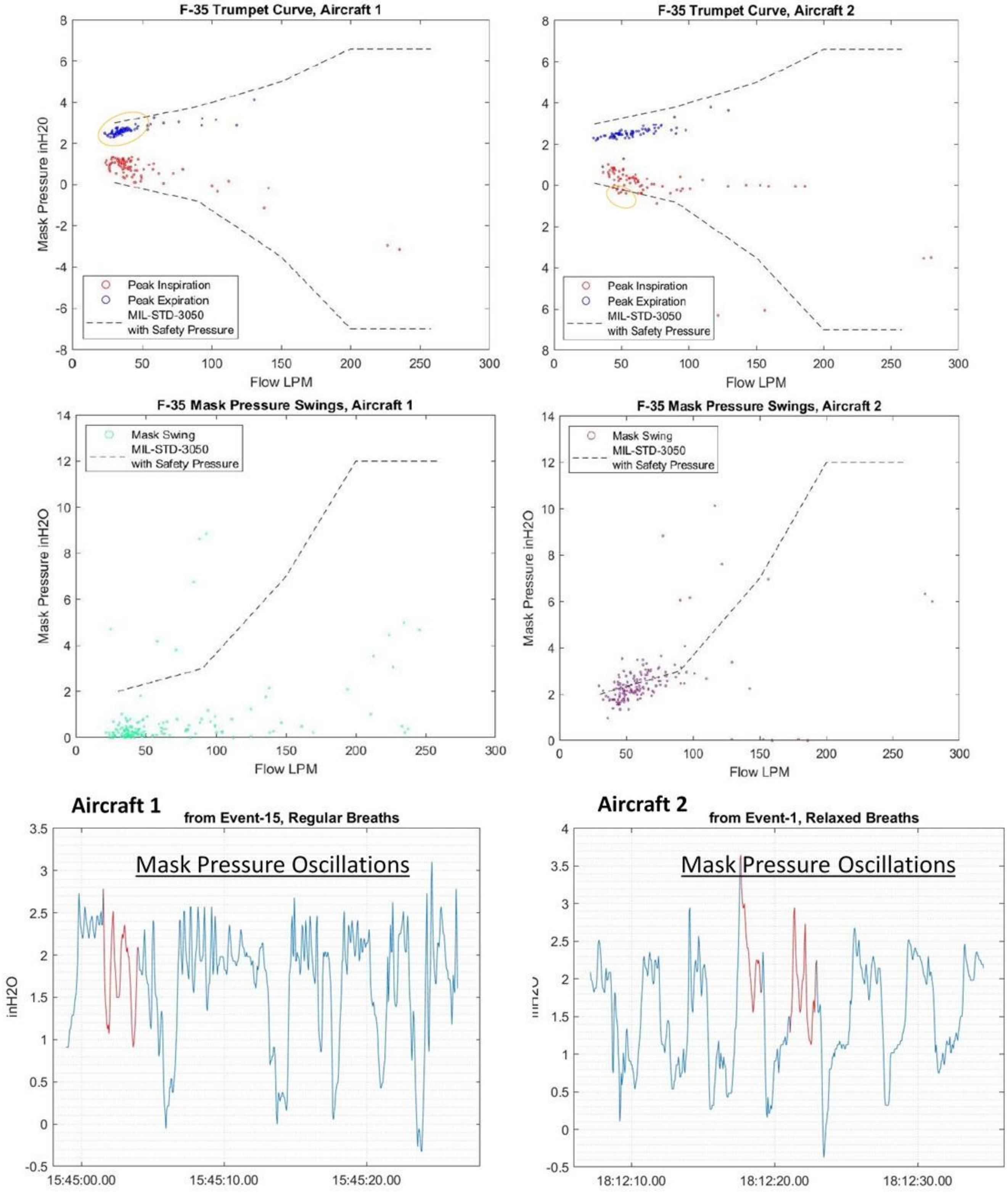


Figure 6.2. MIL-STD 3050 Trumpet Curves (top), MIL-STD 3050 Mask Pressure Swings (middle), Mask Pressure Oscillations (bottom).

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.

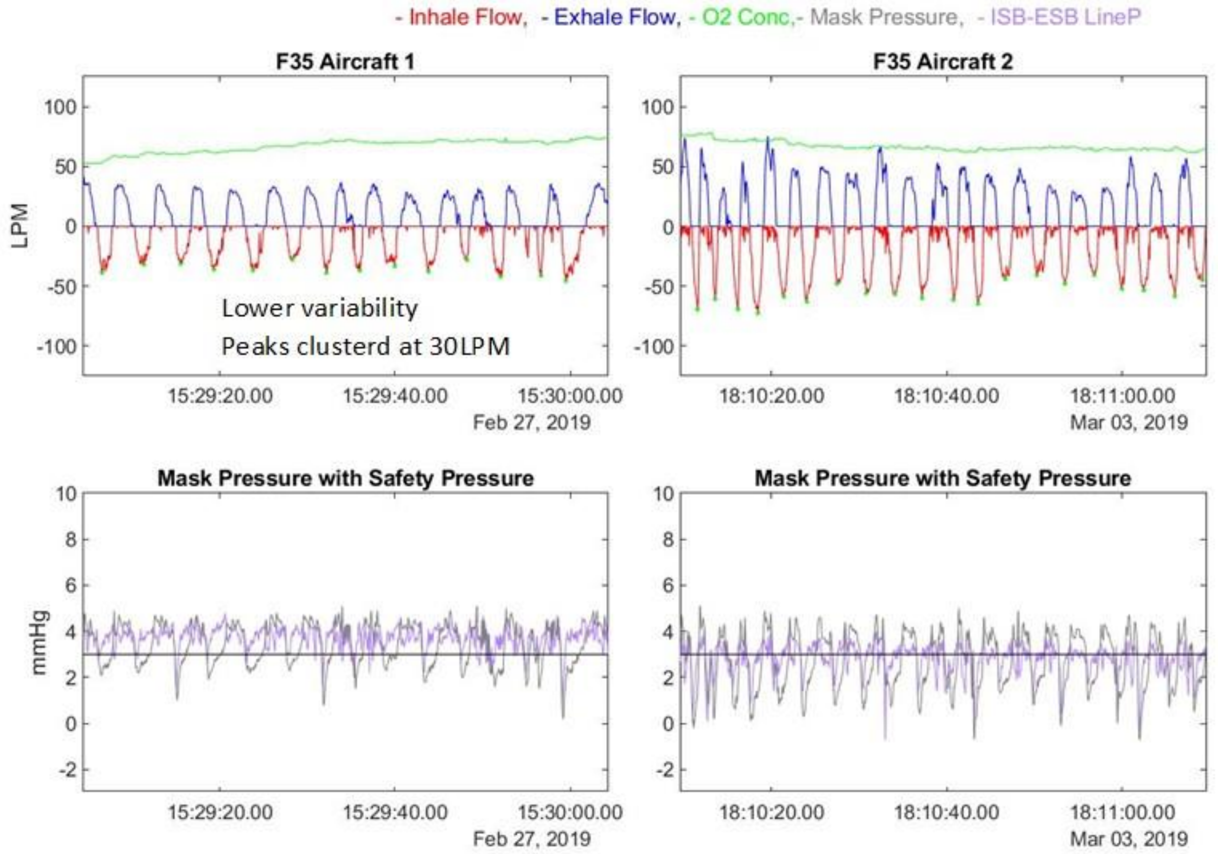
Minute Ventilation: Pulmonary ventilation is the volume of gas per unit time entering the lungs, often defined as Minute Ventilation (MV) in units of Liters/min abbreviated in this section as LPM. MV is a direct product of TV (liters/breath) and respiration rate (breaths/minute). MV requirements are 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.



Segment 1

Aircraft 1
1. Normal Relaxed Breathing
Breaths/min = 14
Peak Insp Flow = 45.40 LPM
Peak Exp Flow = 41.30 LPM
Peak Mask Pressure in = 0.20 mmHg
Peak Mask Pressure out = 5.10 mmH
Minute Ventilation = 8.79 L
Tidal Volume (mean) = 0.63 L
O2 swing = 22.68 %

Aircraft 2
1. Normal Relaxed Breathing
Breaths/min = 20
Peak Insp Flow = 72.40 LPM
Peak Exp Flow = 75.30 LPM
Peak Mask Pressure in = -0.70 mmHg
Peak Mask Pressure out = 5.10 mmHg
Minute Ventilation = 16.36 L
Tidal Volume (mean) = 0.82 L
O2 swing = 16.86 %

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.

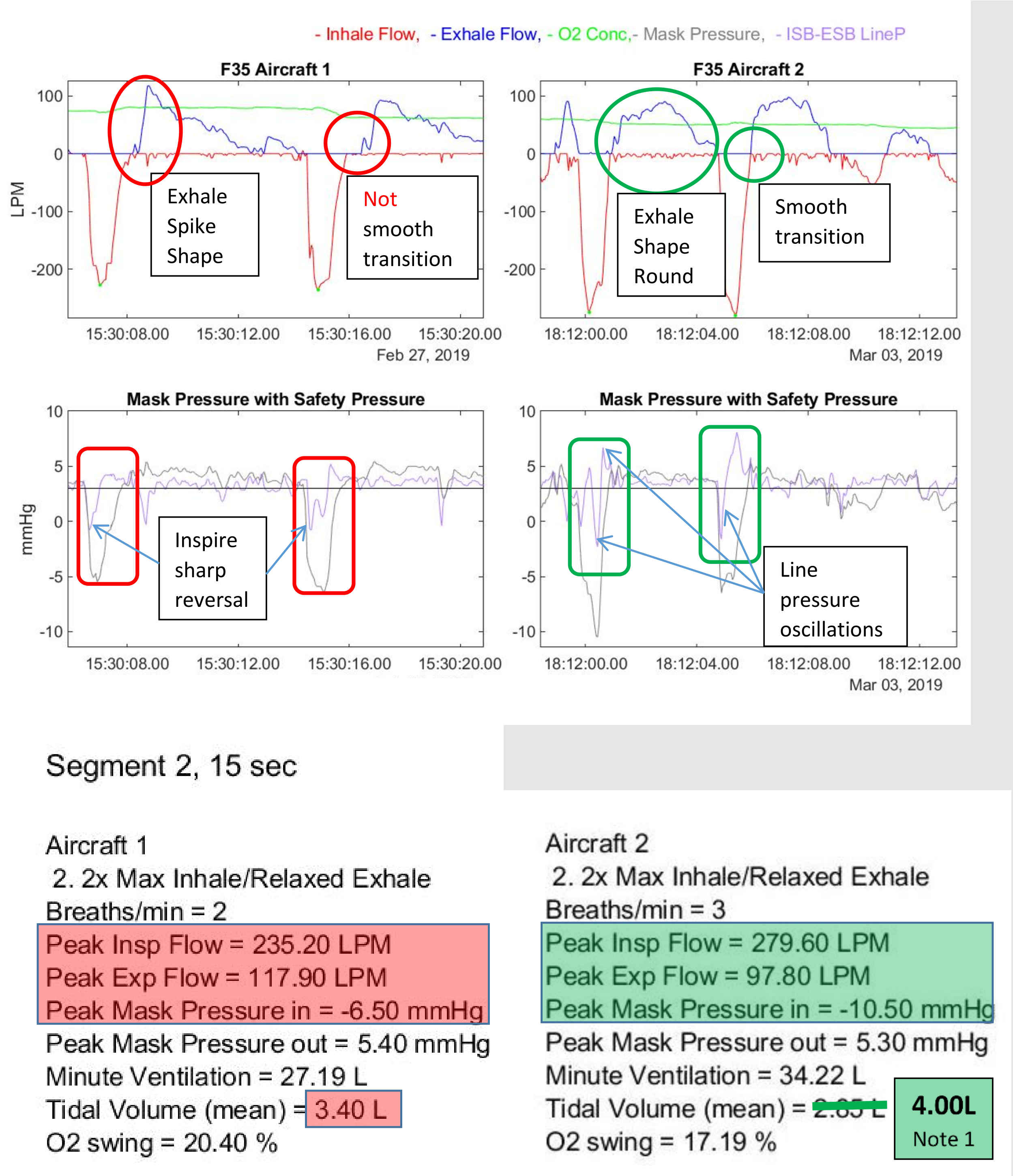
Maximum inhale maneuvers for the two F-35 aircraft allowed means of 3.4 L and 4.l0 L in single breath tidal volumes; although this represents a significant difference between the two aircraft, these numbers are not considered restrictive as the 99th percentile is 2.04 L for real-world flights from the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



Segment 2, 15 sec

Aircraft 1
2. 2x Max Inhale/Relaxed Exhale
Breaths/min = 2
Peak Insp Flow = 235.20 LPM
Peak Exp Flow = 117.90 LPM
Peak Mask Pressure in = -6.50 mmHg
Peak Mask Pressure out = 5.40 mmHg
Minute Ventilation = 27.19 L
Tidal Volume (mean) = 3.40 L
O2 swing = 20.40 %

Aircraft 2
2. 2x Max Inhale/Relaxed Exhale
Breaths/min = 3
Peak Insp Flow = 279.60 LPM
Peak Exp Flow = 97.80 LPM
Peak Mask Pressure in = -10.50 mmHg
Peak Mask Pressure out = 5.30 mmHg
Minute Ventilation = 34.22 L
Tidal Volume (mean) = ~~2.85 L~~ **4.00L** Note 1
O2 swing = 17.19 %

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

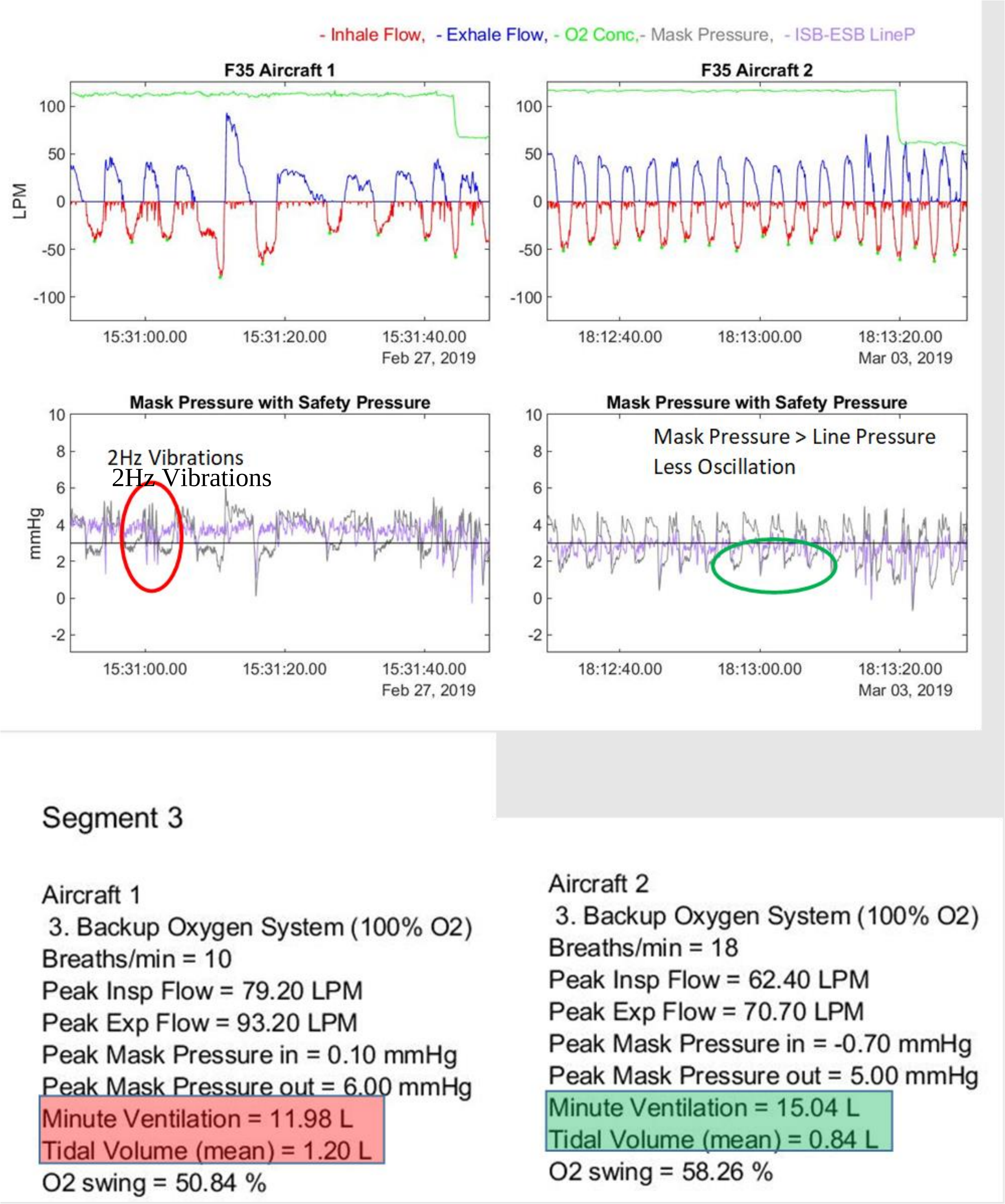
6.5 Effects of Backup Oxygen System (BOS)

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.



Segment 3

Aircraft 1
3. Backup Oxygen System (100% O2)
Breaths/min = 10
Peak Insp Flow = 79.20 LPM
Peak Exp Flow = 93.20 LPM
Peak Mask Pressure in = 0.10 mmHg
Peak Mask Pressure out = 6.00 mmHg
Minute Ventilation = 11.98 L
Tidal Volume (mean) = 1.20 L
O2 swing = 50.84 %

Aircraft 2
3. Backup Oxygen System (100% O2)
Breaths/min = 18
Peak Insp Flow = 62.40 LPM
Peak Exp Flow = 70.70 LPM
Peak Mask Pressure in = -0.70 mmHg
Peak Mask Pressure out = 5.00 mmHg
Minute Ventilation = 15.04 L
Tidal Volume (mean) = 0.84 L
O2 swing = 58.26 %

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

6.6 Effects of Defog On

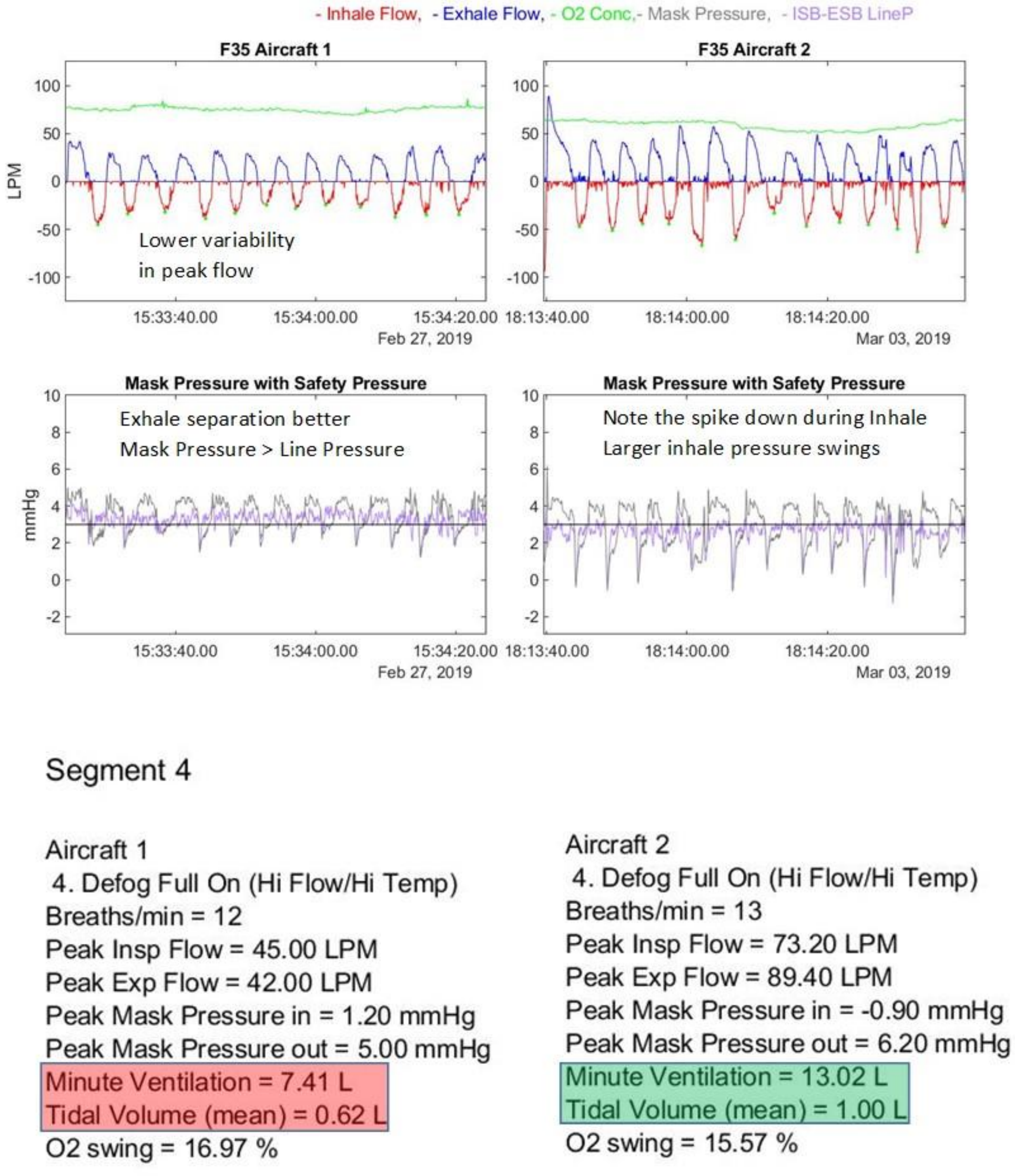
The Defog system in the F-35 controls the temperature, distribution, and flow of the air entering the cockpit. The air temperature is increased the maximum amount, diverted to the canopy, and the flow is increased in order to defog the canopy or preheat it in order to prevent canopy fogging. Selecting 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.



Segment 4

Aircraft 1
4. Defog Full On (Hi Flow/Hi Temp)
Breaths/min = 12
Peak Insp Flow = 45.00 LPM
Peak Exp Flow = 42.00 LPM
Peak Mask Pressure in = 1.20 mmHg
Peak Mask Pressure out = 5.00 mmHg
Minute Ventilation = 7.41 L
Tidal Volume (mean) = 0.62 L
O2 swing = 16.97 %

Aircraft 2
4. Defog Full On (Hi Flow/Hi Temp)
Breaths/min = 13
Peak Insp Flow = 73.20 LPM
Peak Exp Flow = 89.40 LPM
Peak Mask Pressure in = -0.90 mmHg
Peak Mask Pressure out = 6.20 mmHg
Minute Ventilation = 13.02 L
Tidal Volume (mean) = 1.00 L
O2 swing = 15.57 %

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.

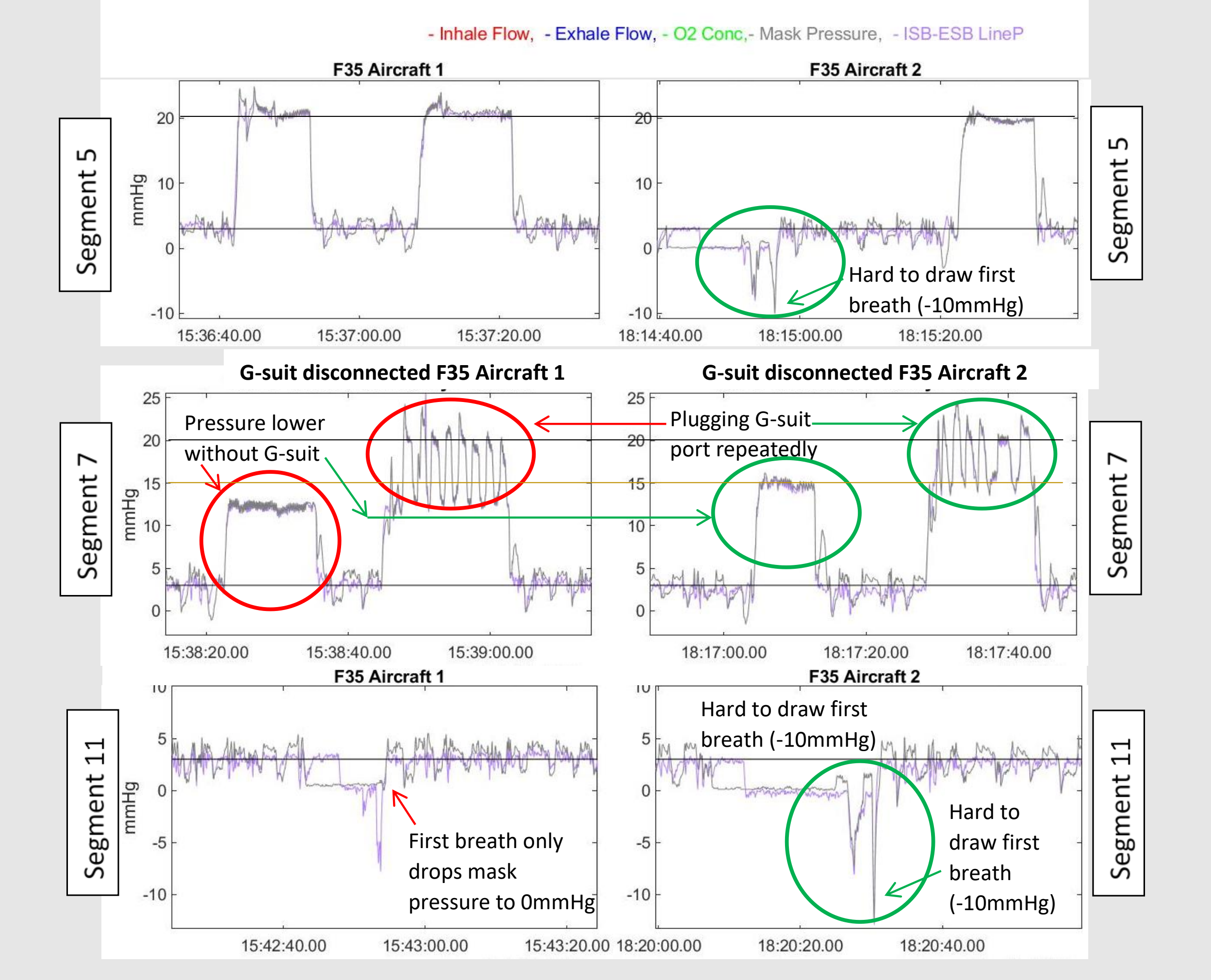


Figure 6.8. PTT with G-suit connected (top graph), PTT with G-suit disconnected (middle graph), Mask doffing with G-suit disconnected (bottom graph) for both F-35 aircraft during the respective Segments as labeled. (Top Right graph) also has Mask Doffing with G-suit connected.

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.

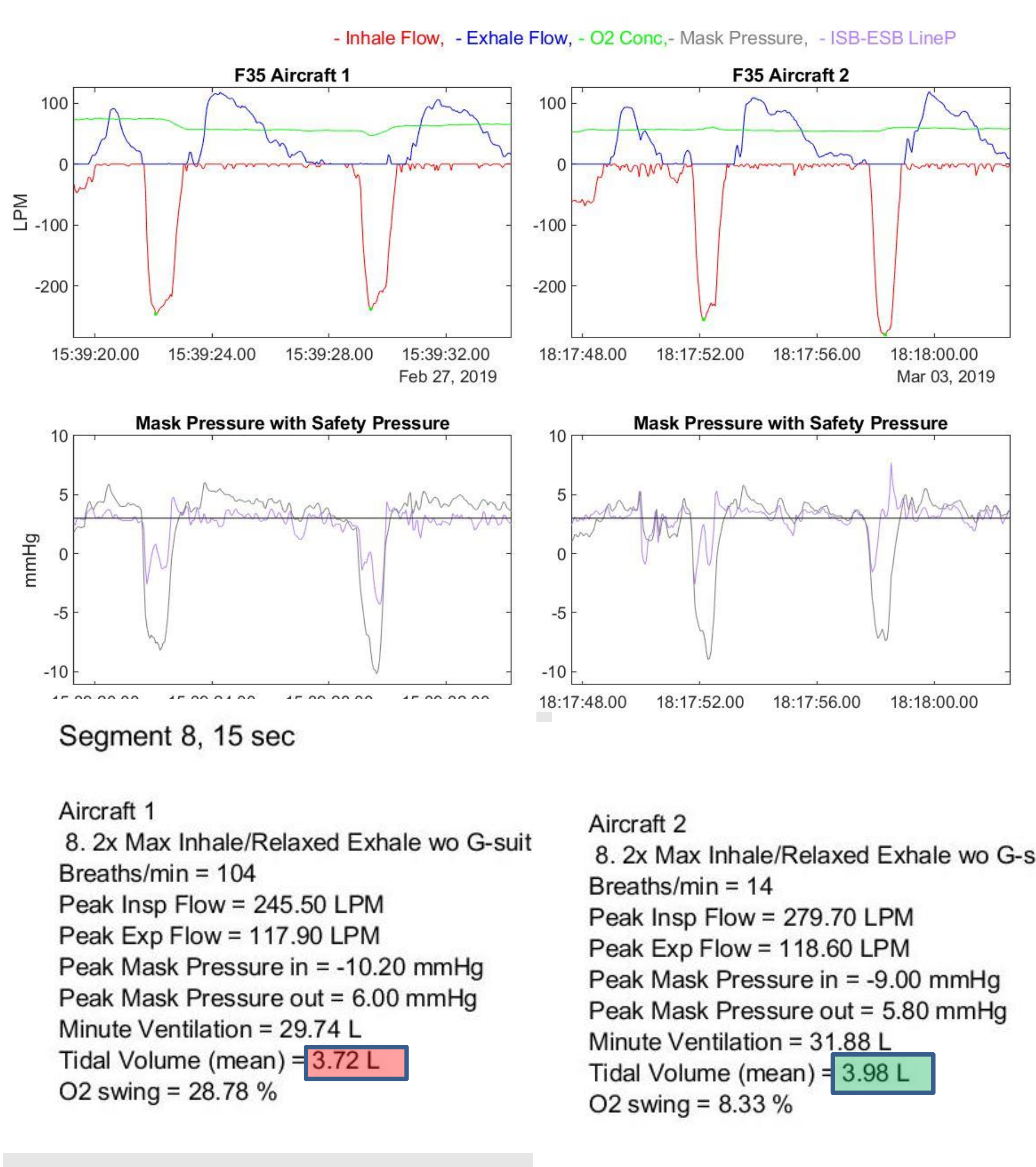
On Aircraft 1, the mean TV was 3.72. TV increased .32L above the 3.4L mean in Segment 2 with the G-suit connected. This was consistent with the pilots report of easier breathing with the G-suit disconnected. The breathing dynamics during exhale more closely resemble Aircraft 1. They are no longer characterized 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)

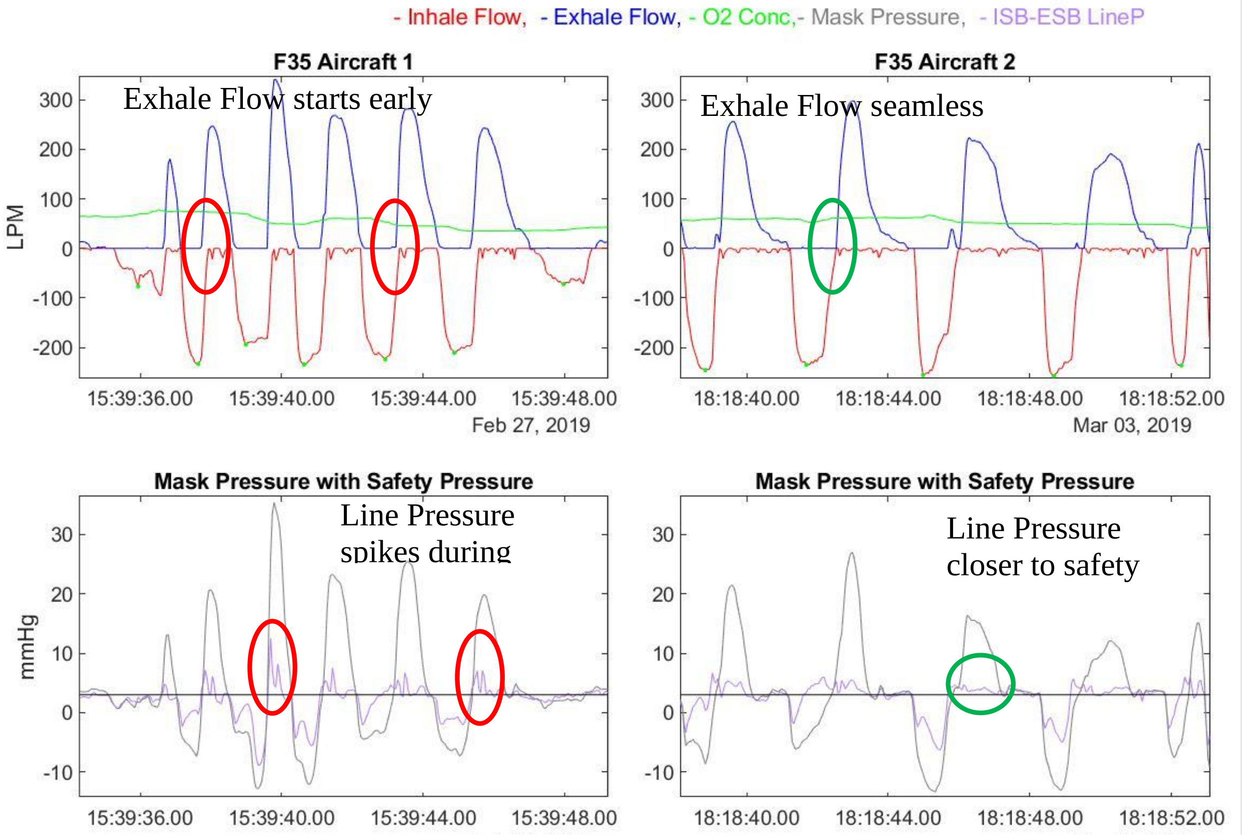
During Segment 9, the goal was not a maximal and repeatable inhale, but rather a continuous demand for a maximum amount of air. Instead of a relaxed exhale, here the exhales are forceful. Basically the goal was maximum effort, continuous breathing for 15 seconds, with no attempt to have a specifically 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.

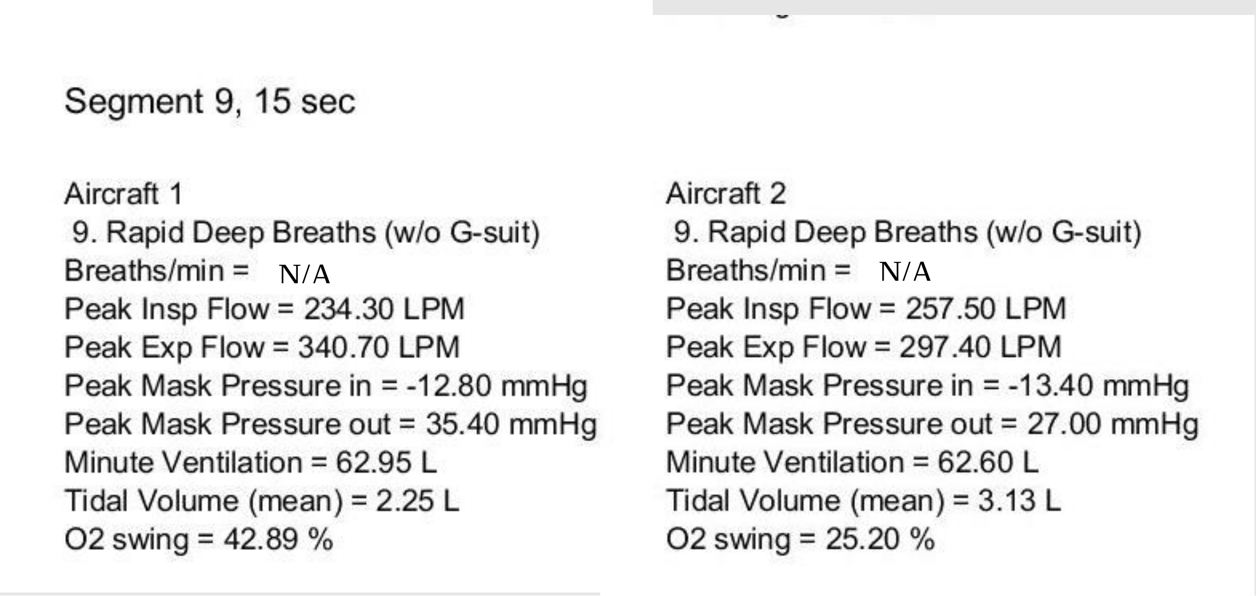


Exhale Flow starts early

Exhale Flow seamless

Line Pressure spikes during

Line Pressure closer to safety



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.

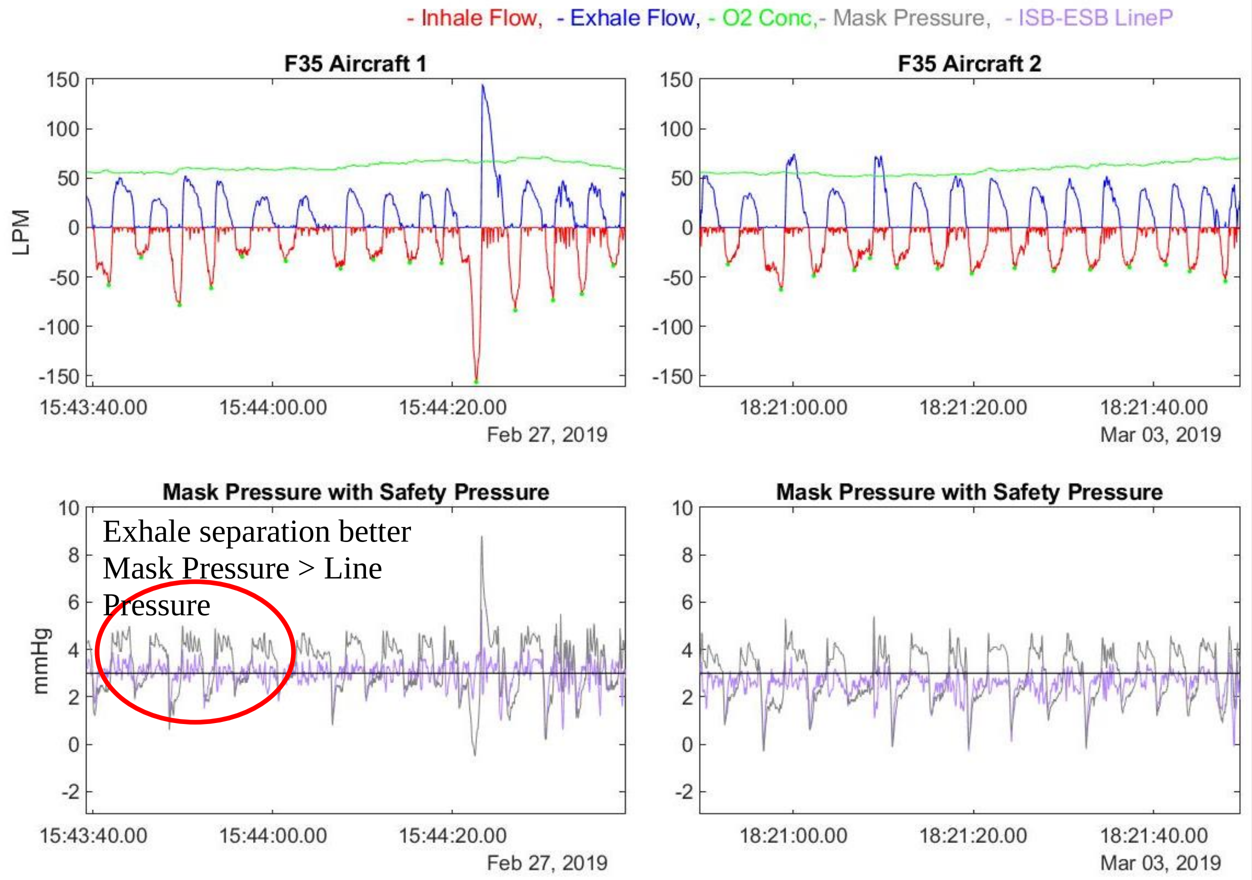
On Aircraft 1, the mean TV was .93L, the MV was 13.92L, and the Respiration Rate (RR) 15 breaths/min. The breathing dynamics are characterized by significantly improved separation between mask pressure and line pressure during exhale, and a concomitant increase in TV and MV. Compared to baseline in Segment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

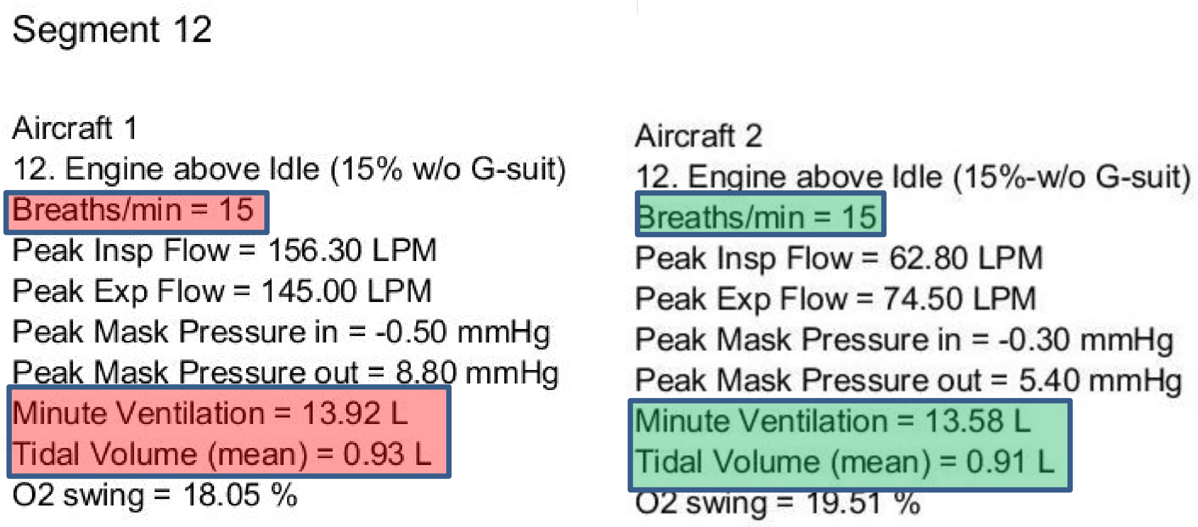
On Aircraft 2, the mean TV was .91L, the MV was 13.58L, and the RR was 15 breaths/min. Compared to baseline in Segment 1, TV is increased from .82L, respiration rate is decreased from 20 breaths/min, and overall MV is decreased from 16.36L. See Figure 6.11.

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.

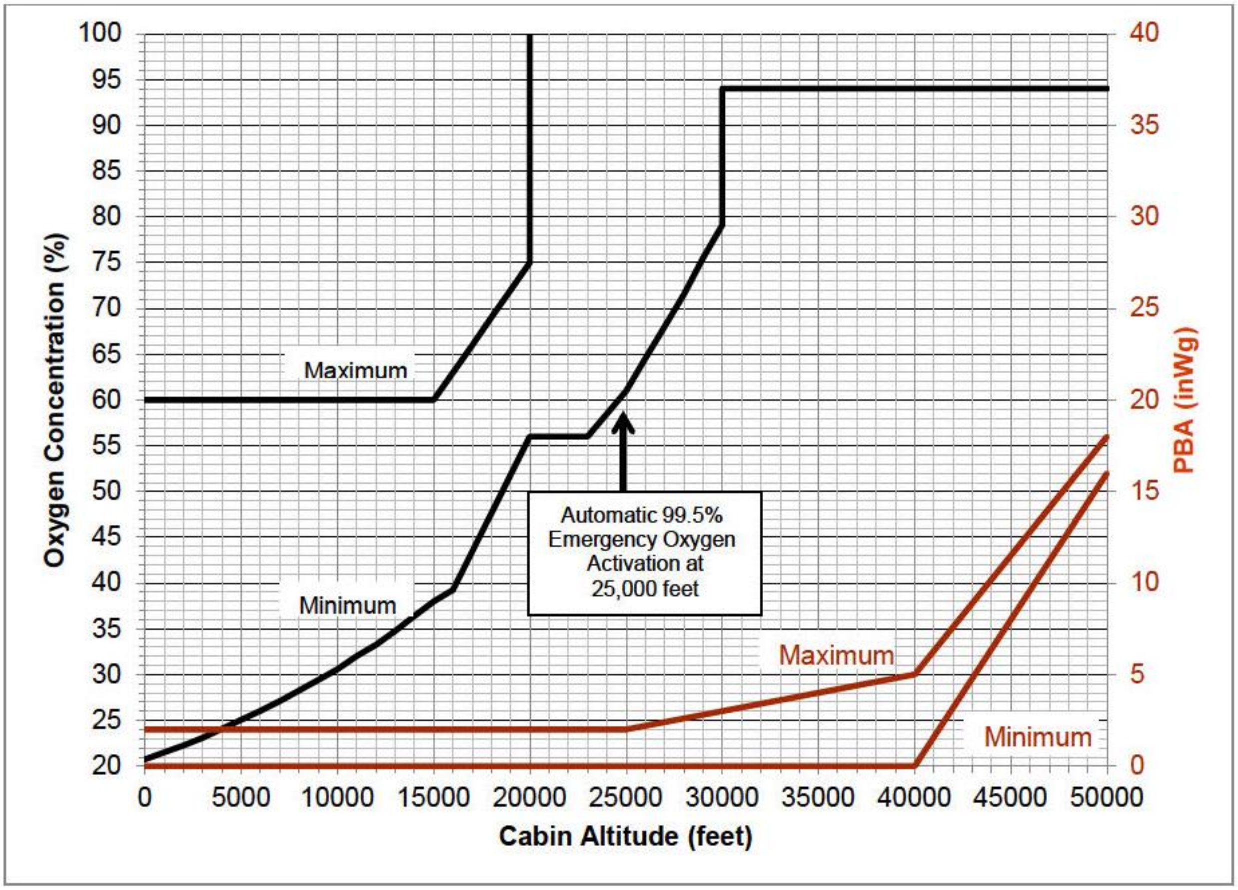


Figure 6.12. O_2 concentrations and regulator pressure schedule for an aircraft flying to 50.000 feet with a 5 psi differential pressure cabin.

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)

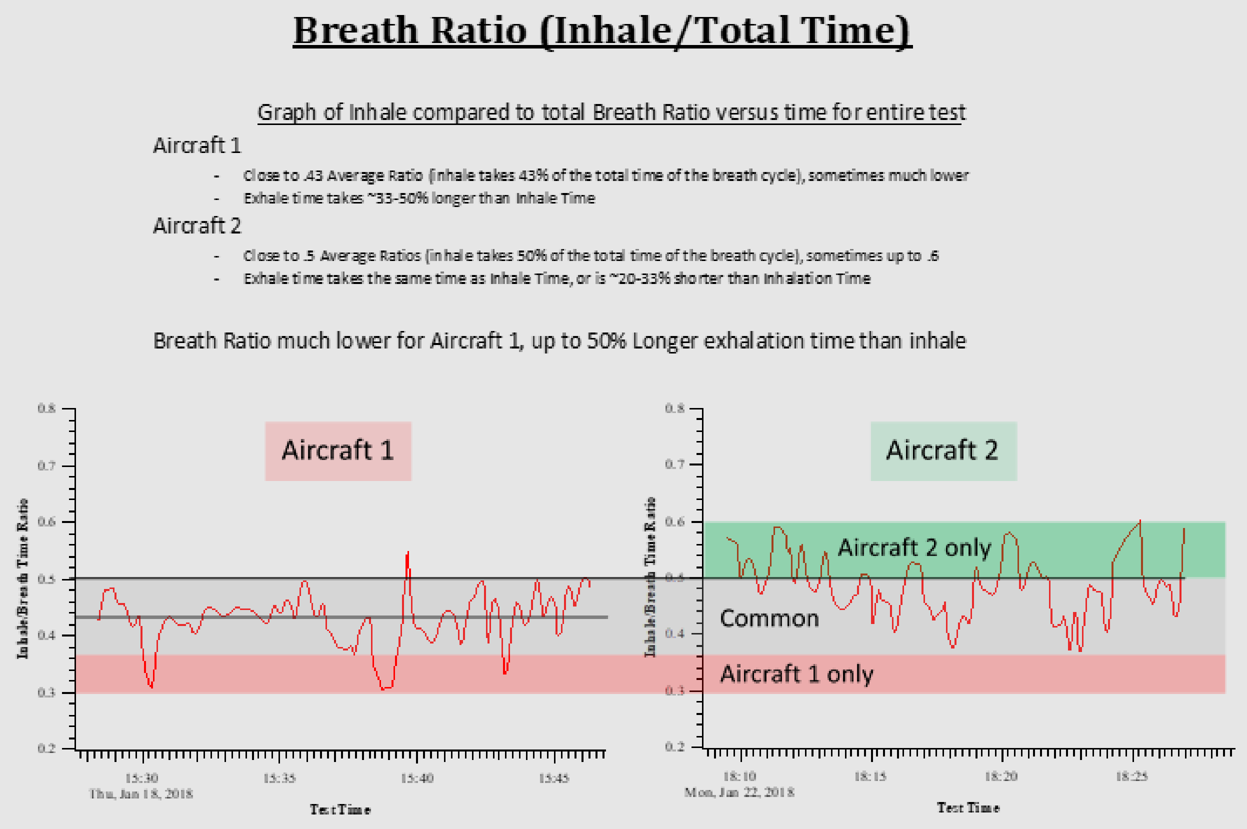
Breath Ratios are another general metric, applied here to assess changes in the pilots breathing dynamic. These breath ratios show a systematic difference between the two aircraft characterized by longer exhale times on Aircraft 1. Inhale to Exhale ratios are commonly used in respiratory physiology. 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.



Breath Ratio (Inhale/Total Time)

Graph of Inhale compared to total Breath Ratio versus time for entire test

Aircraft 1
- Close to .43 Average Ratio (inhale takes 43% of the total time of the breath cycle), sometimes much lower
- Exhale time takes ~33-50% longer than Inhale Time

Aircraft 2
- Close to .5 Average Ratios (inhale takes 50% of the total time of the breath cycle), sometimes up to .6
- Exhale time takes the same time as Inhale Time, or is ~20-33% shorter than Inhalation Time

Breath Ratio much lower for Aircraft 1, up to 50% Longer exhalation time than inhale

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.

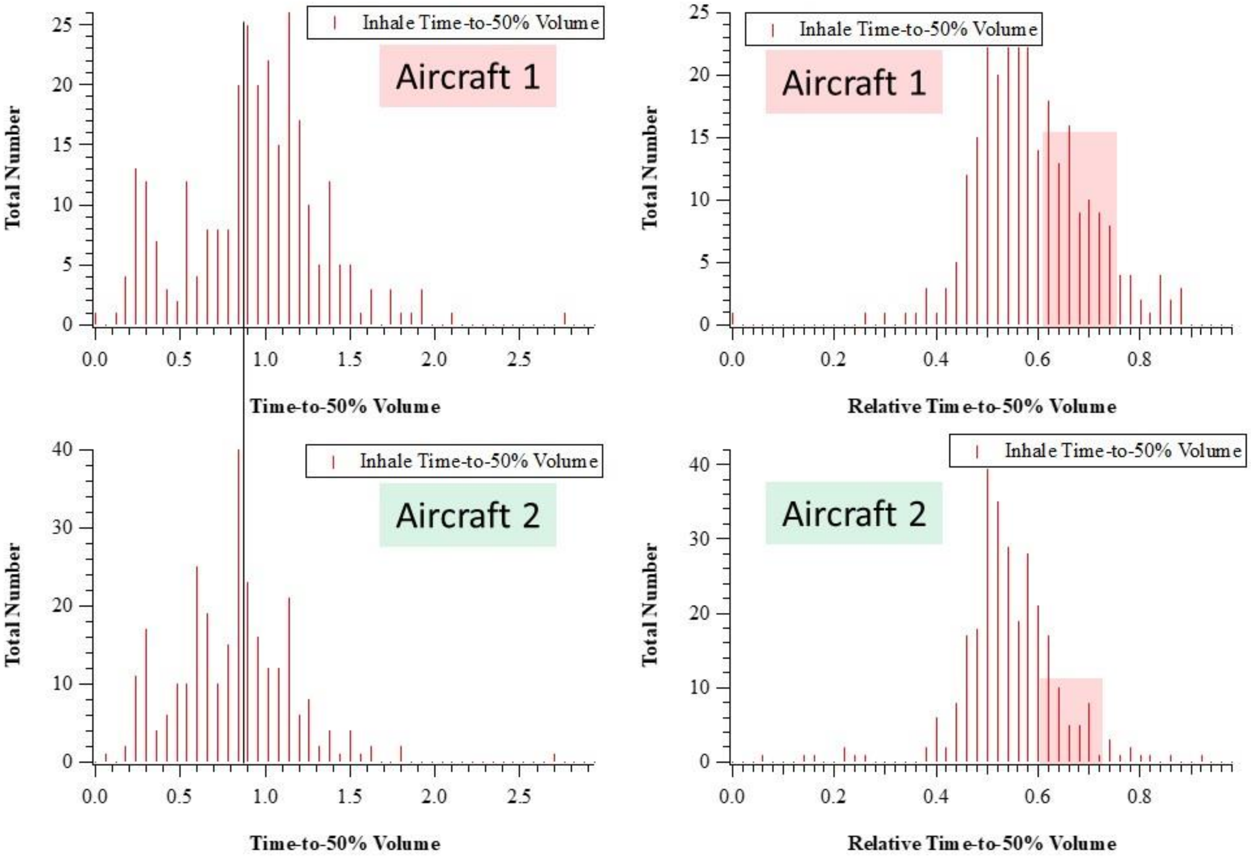
Because of the extensive lag in the flow seen during the start of inhale, and the overshoot in pressure/flow during the second half of the breath, this was considered as a way to gauge the overall impact of those dynamics and quantify their magnitude and frequency. Simply timing how long it takes to 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.



<u>Histograms of Inhale breath time-to-50%</u>

Aircraft 1

1.15s Inhale Peak Time

40% above .6 Relative Time-to-50%

Aircraft 2

.85s Inhale Peak Time

20% above .6 Relative Time-to-50%

- Inhale time-to-50% is .3 seconds longer (33% longer) on Aircraft 1
- Inhale greater than .6 relative Time-to-50% happens 20% more on Aircraft 1
- This is an indication of slow response (lag) in the system during inhalation

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.

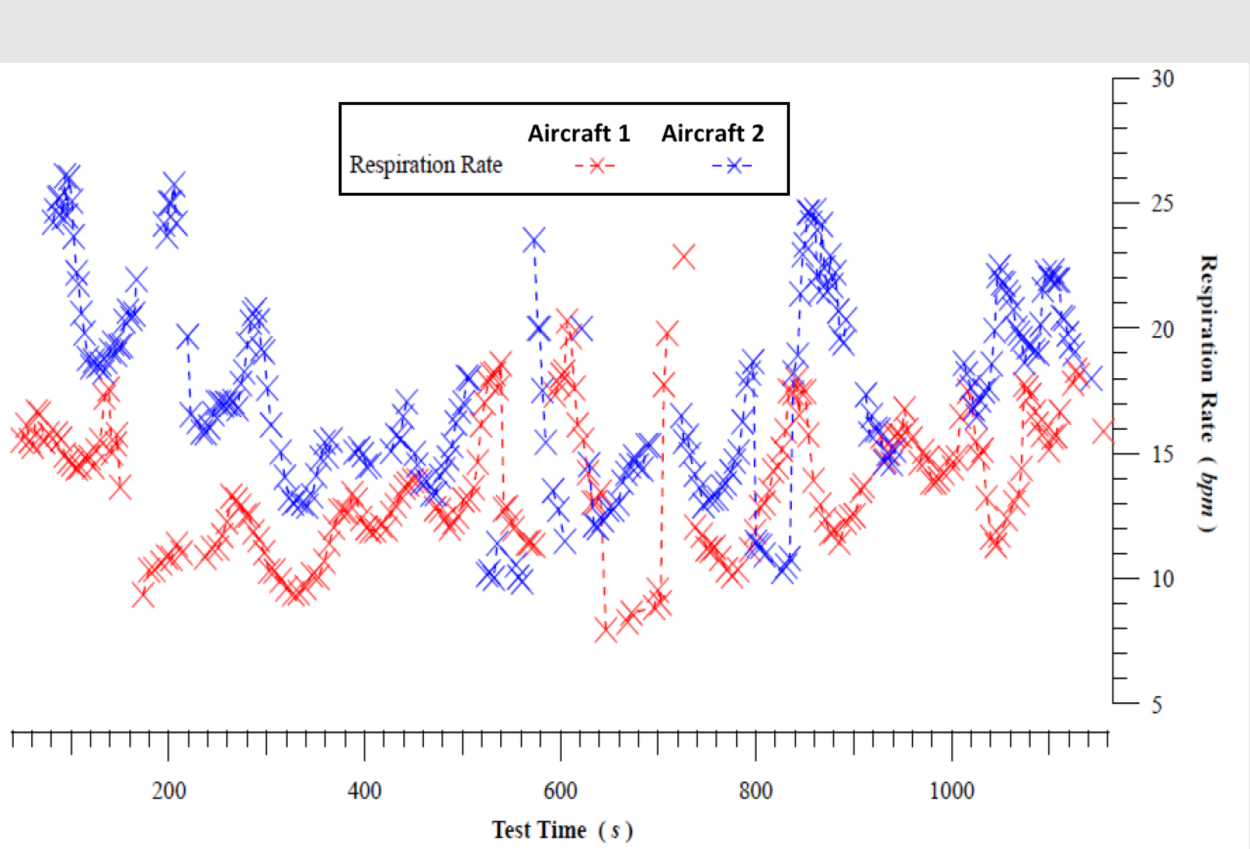


Figure 7.4. Pilot Respiration rate from measured data for the two F-35 aircraft. Note that the pilot in Aircraft 1 consistently has less respiration than in Aircraft 2.

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.

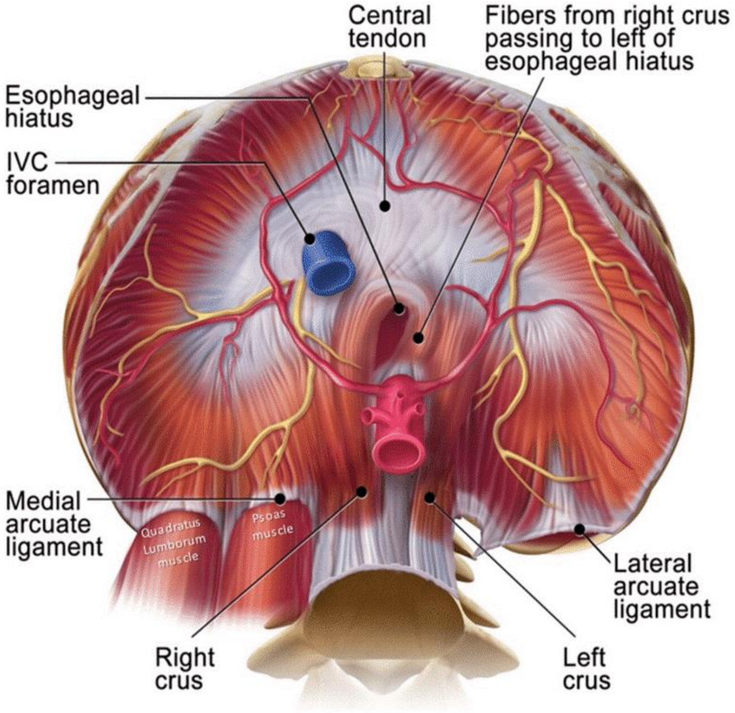


Figure 8.1. Diaphragm Anatomy

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.

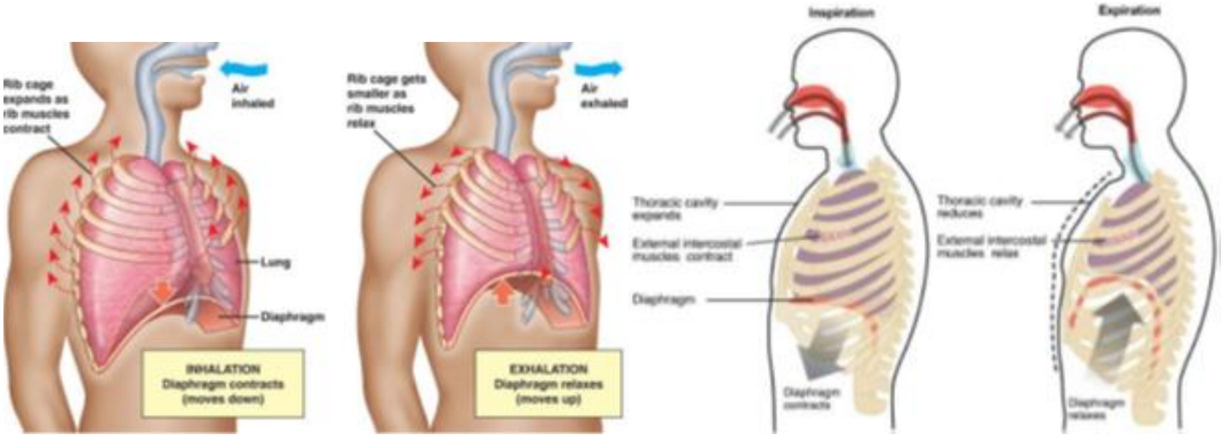


Figure 8.2. Inspiration and Expiration Muscular Mechanics

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.

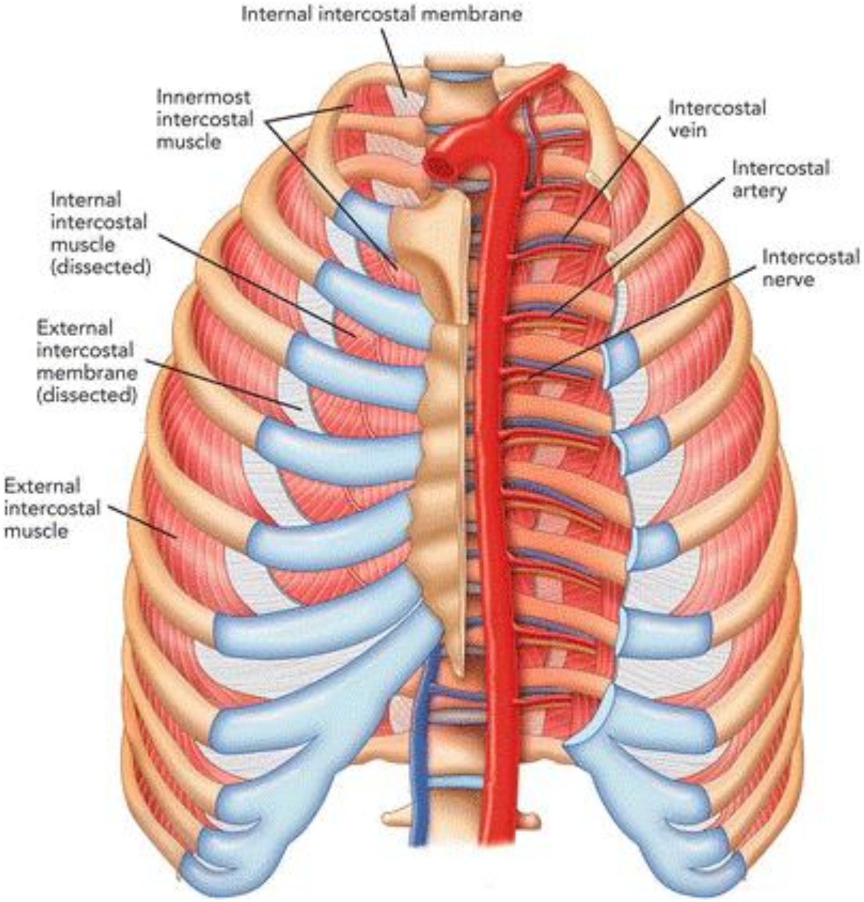


Figure 8.3. Intercostal Muscles

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.

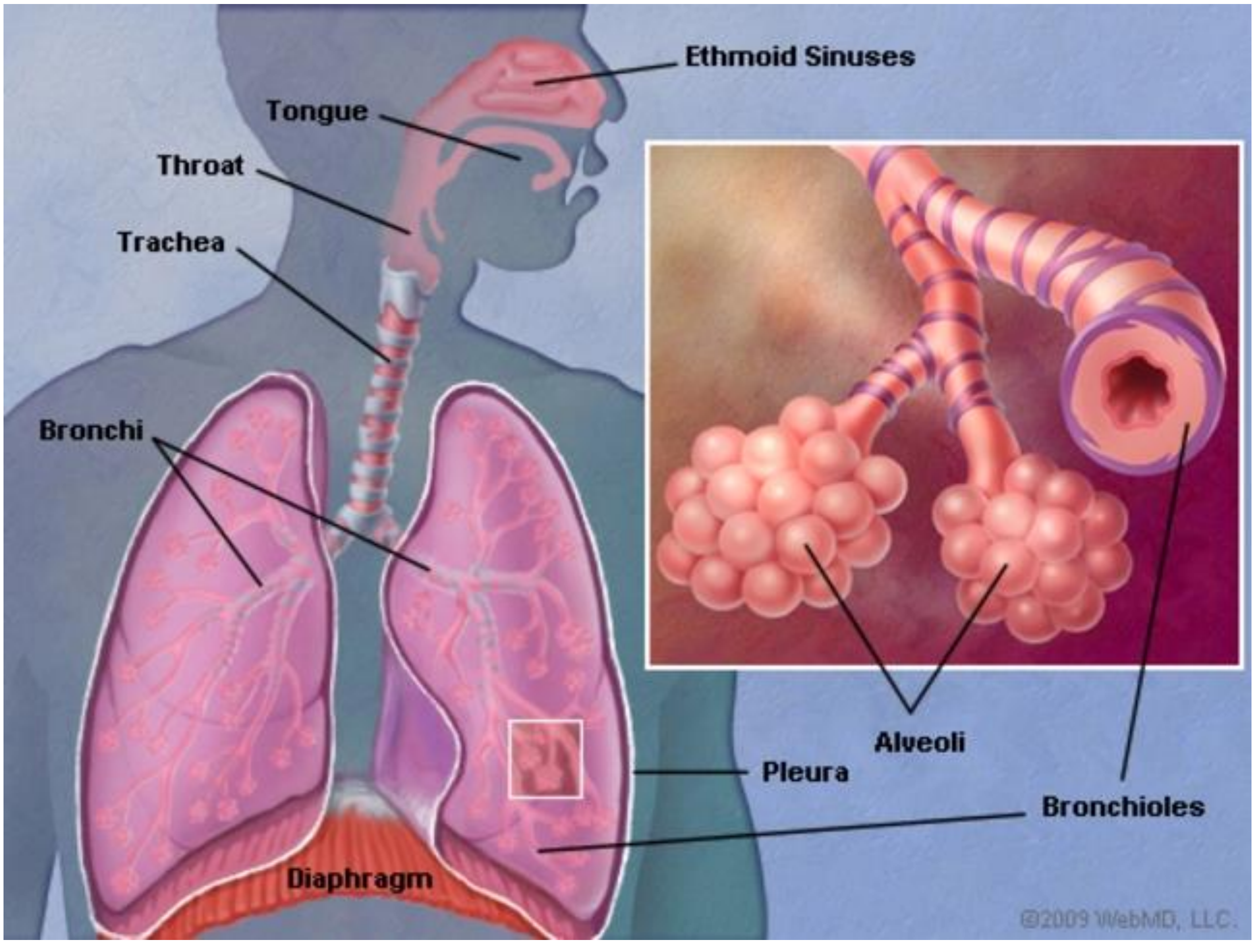


Figure 8.4. Pulmonary (Lung) Anatomy

Dead Space: 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.

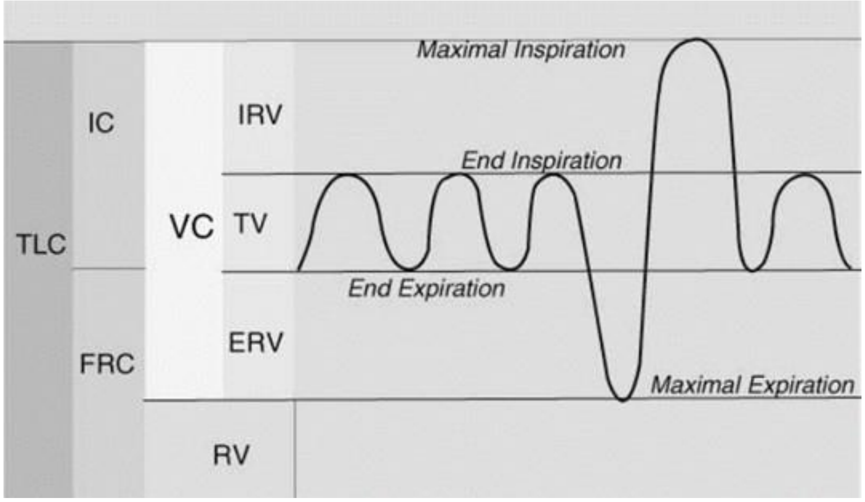


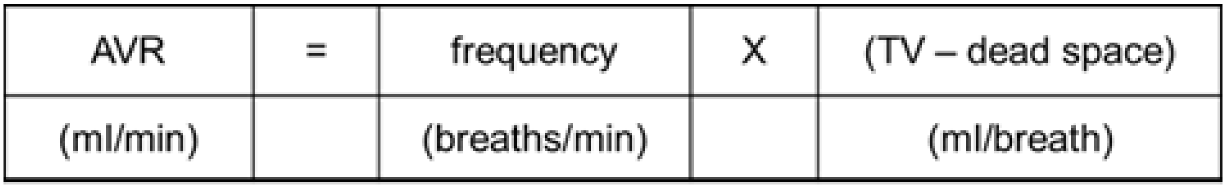
Figure 8.5. Pulmonary Volumes

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.

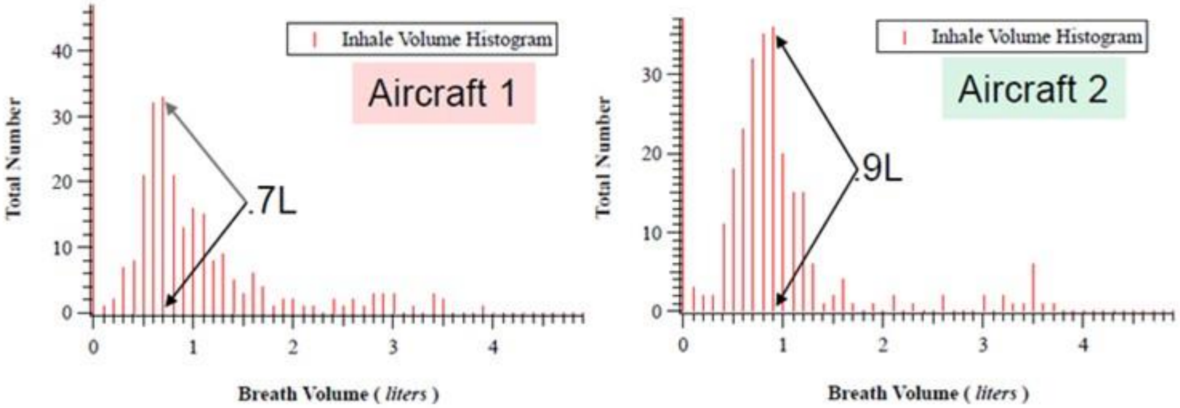


Figure 8.6. Reduced TV on Aircraft 1 compared to Aircraft 2

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.

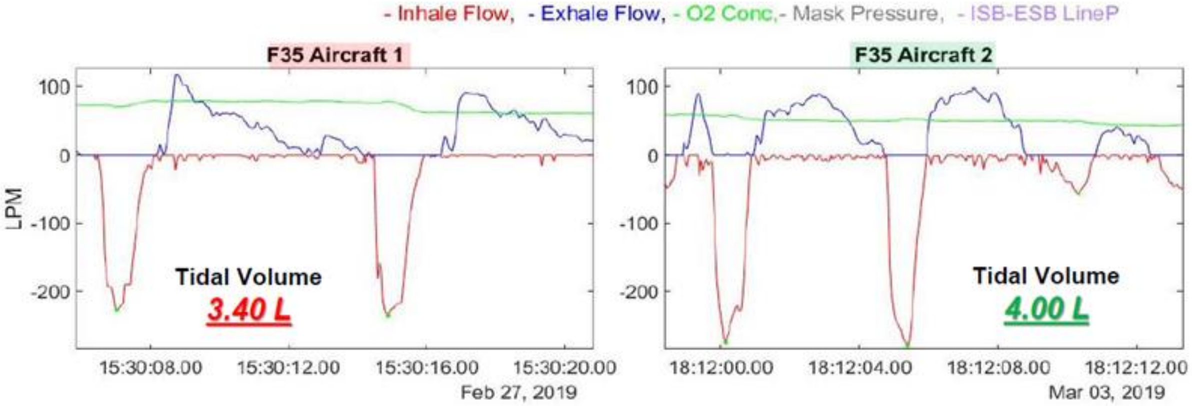


Figure 8.7. Reduced TV during Maximum Inhale on Aircraft 1 compared to Aircraft 2

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).

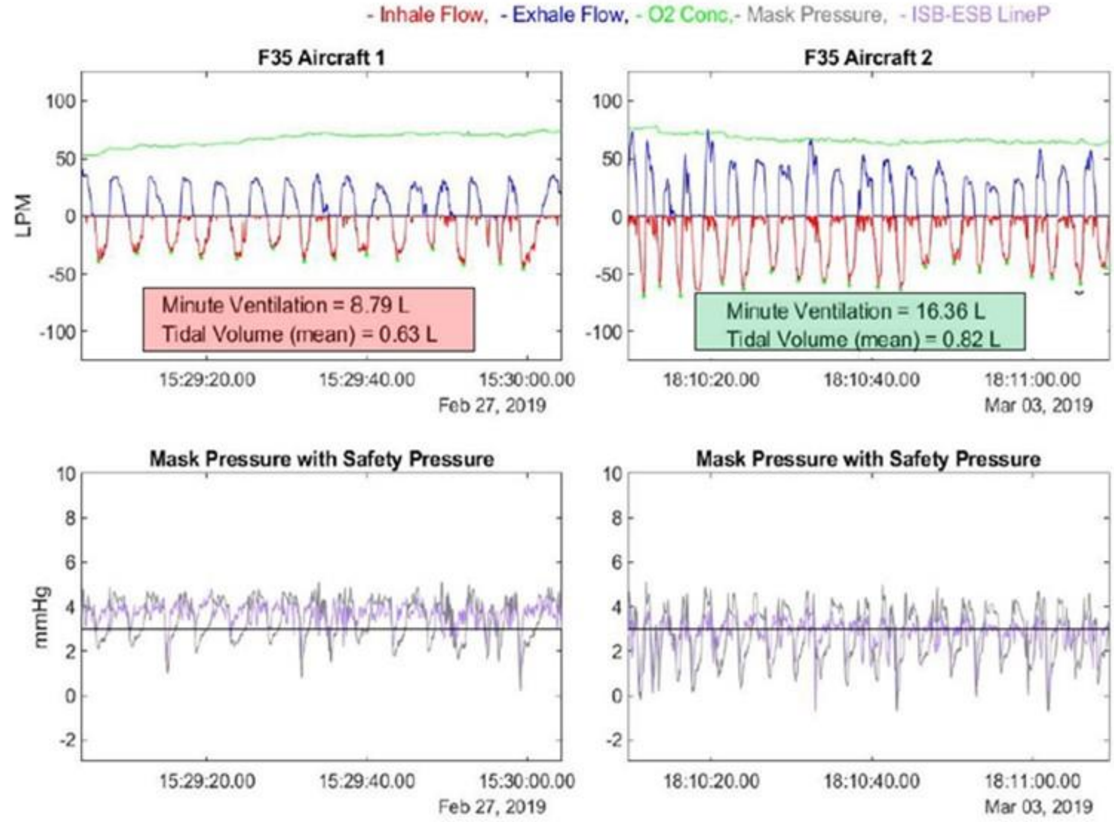


Figure 8.8. Normal Relaxed Breathing for Aircraft 1 and Aircraft 2

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.

<u>Alveolar overdistension</u>: 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:

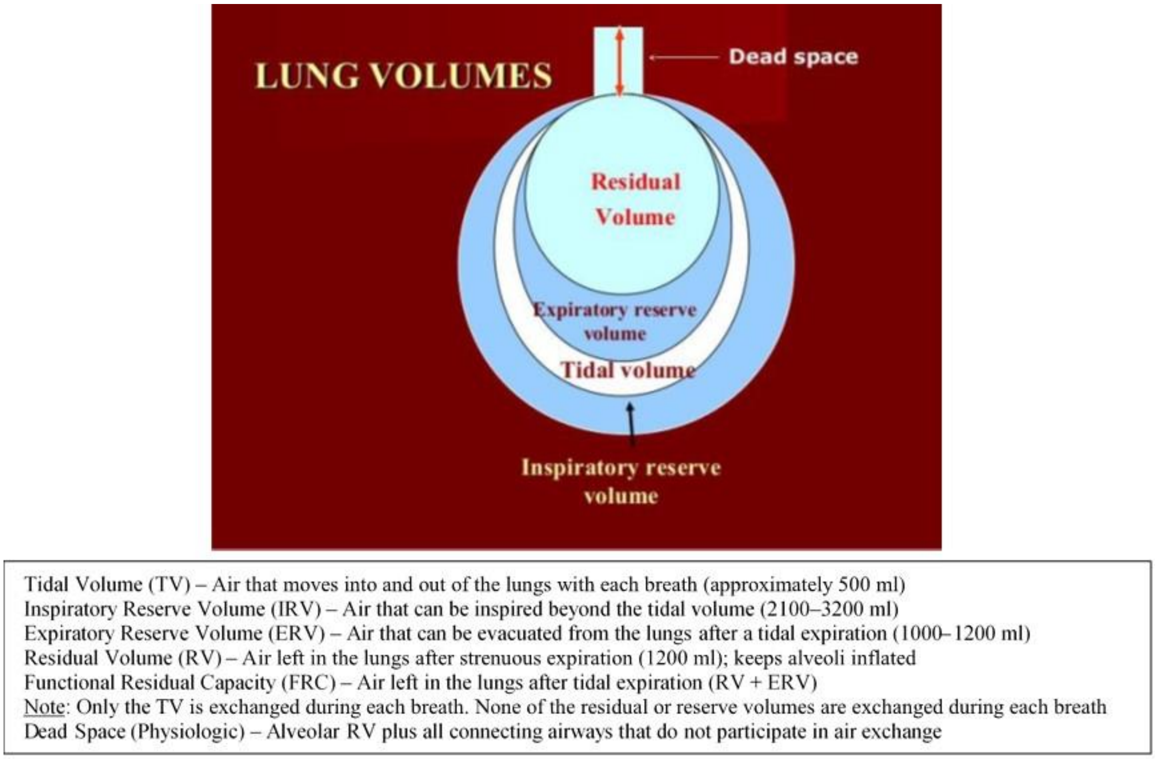
The level of flow restriction observed in Aircraft 1 by estimate appears to be moderate, as judged by the adaptive nature of the pilot’s response and the lack of any reported resistance by the pilot. Trained aircrew, under most circumstances, would be unaware of the effects of increased resistance in 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.

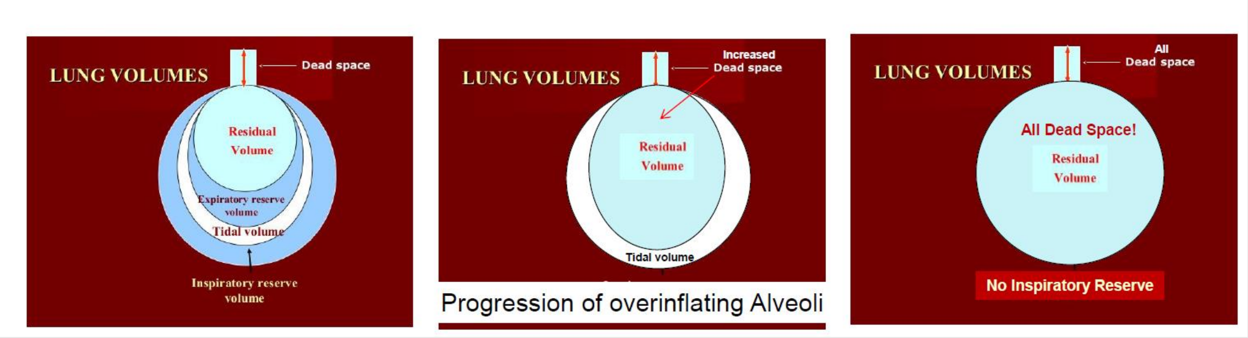


Figure 8.10. Normal Relaxed Breathing for Aircraft 1 and Aircraft 2

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.

O_2 concentrations 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.

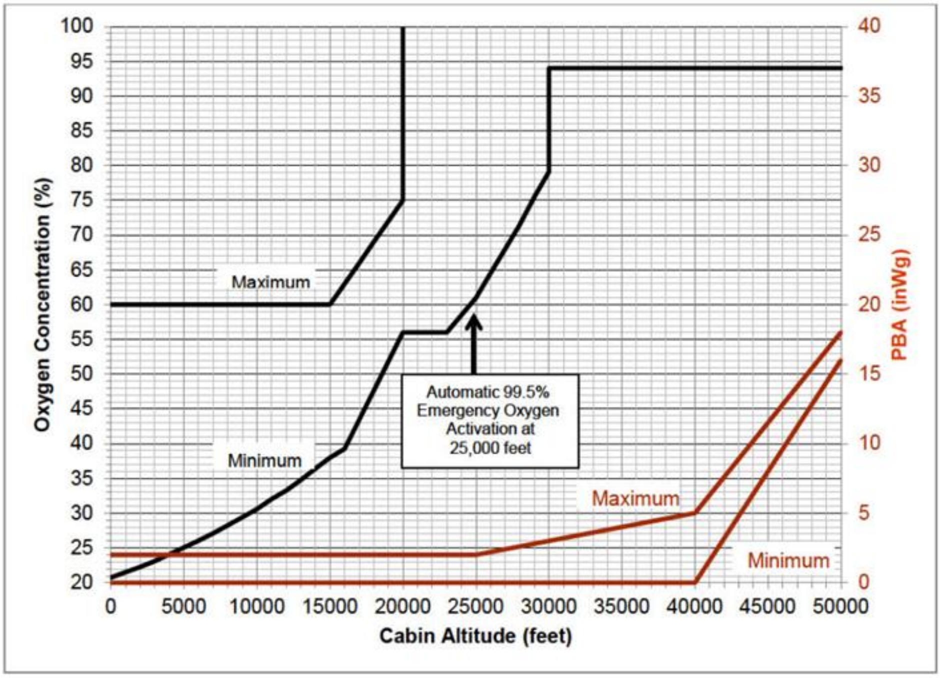


Figure 8.11. O_2 concentrations and regulator pressure schedule for an aircraft flying to 50,000 feet with a 5 psi differential pressure cabin.

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)	[51%]	[58%]
[Expected due to system change to BOS]		
4) Defog Full On (Hi Flow/Hi Temp)	17%	16%
5) 2x Press-to-Test (Mask Off in #2 only)	18%	39%*
(*Due to Mask Off free flow)		
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	17%	[49%]
[Expected due to system change to 100%]		
14) Press-to-Test (BOS – 100% Oxygen)	63%	56%
15) 10 timed breaths in #1 / Mask Off in #2	15%	25%*
(*Due to Mask Off free flow)		
Average oxygen change per Aircraft	27%	22%
[Excluding 3, 13 due to 100% oxygen]		
(*Excluding 5, 15 due to dissimilar points)		

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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Appendix 8: Pilot Breathing Assessment (PBA) Considerations on NESC's F/A-18 PE Report (2017) and Other Issues

The PBA was undertaken to use NASA aircraft as testbeds to instrument, measure, analyze study and document the physical phenomena behind pilot physiological episodes. As previously stated by the NESC in 2017, the physiological episodes experienced by F/A-18 pilots were found to be the result of system-level weaknesses and failures to consider the entire aircraft and pilot as an integrated whole, as well as the aircraft-pilot interactions as integrated components in a critical human life-sustaining system. The details of these findings were documented in the NESC report on the F/A 18 and E/A-18 Fleet Physiological Episodes (NESC, 2017; Chapter 10). The work done by the Pilot Breathing Assessment as documented in this report is an effort to further that work by showing a path forward for instrumenting and measuring dynamic system interactions such that the inherent shortcomings may be identified and addressed at a system level.

2017's Key Recommendations and PBA Updates

The 2017 report presented a number of key recommendations. These recommendations are discussed below, updated with knowledge gained from the PBA:

1. **2017 Recommendation #1:** Pilot Breathing Needs to Be Measured
    a. F/A-18 Report Key Recommendation: Measure parameters that directly assess human health and performance. Make measurements in the cabin environment whenever possible.
    b. Related PBA actions: The entire PBA project was focused on measuring human health and performance in the cabin environment.
    c. PBA 2020 assessment: PBA developed a standard method for measuring human health and performance in the cabin environment. PBA developed a standard method for assessing data.
2. **2017 Recommendation #2:** Cabin Pressure Needs to be Measured
    a. F/A-18 Report Key Recommendation: Measure cockpit pressure and compare pressure profiles for PE flights to pressure profiles for non-PE flights.
    b. Related PBA actions: PBA measured cockpit pressure, mask pressure, delta pressure.
    c. PBA 2020 assessment: PBA identified breathing system interactions related to pressure, especially cabin pressure fluctuations in the 0.1 – 1.0 Hz frequency range.
3. **2017 Recommendation #3:** Investigate the statistical connection between VOC levels at OBOGS outlets and PE rates
    a. F/A-18 Report Key Recommendation: Establish VOC testing at OBOGS outlet on all F/A-18 model aircraft to further evaluate the association between VOC level and PE rate found in the Growler samples.
    b. PBA actions: PBA did not measure VOC levels at OBOGs outlets. PBA testing was performed on legacy Hornets with LOX. PBA did identify Breathing System Disruptions (BSDS) for jets with low and variable ECS supply pressure
    c. PBA 2020 assessment: Elevated levels of VOCs at OBOGS outlet correlate with low and variable ECS pressure. PBA recommends closer look at VOC trends.

    VOCs should not be evaluated from the perspective of chemical toxicity – VOCs should be evaluated as in indication of low and variable ECS pressure. If ECS pressure is directly measured, evaluating VOCs is not necessary

4. **<u>2017 Recommendation #4:</u>** Learn why some jets have more cabin pressure fluctuations
    a. <u>F/A-18 Report Key Recommendation:</u> Recommend taking further steps to validate and apply the NASA cabin pressure model.
    b. <u>PBA actions:</u> PBA found breathing system interactions occur involving cabin pressure fluctuations.
    c. <u>PBA 2020 assessment:</u> PBA recommends reducing the number and magnitude of cabin pressure fluctuations, especially those with a frequency similar to inhalation/exhalation cadence. PBA additionally recommends avoiding safety pressure if possible, because cabin pressure fluctuations cause greater disruption to systems that maintain positive pressure in the mask.
5. **<u>2017 Recommendation #5:</u>** Collect and analyze data in a systematic way – make data sets as comprehensive as possible
    a. <u>F/A-18 Report Key Finding:</u> Determine the full necessary capability and optimal organizational relationships and alignments to support fleet-level data analysis throughout the operational life of all F/A-18 variants.
    b. <u>PBA actions:</u> The entire PBA project was focused on developing a database that is comprehensive and can be analyzed in a systematic way
    c. <u>PBA 2020 assessment:</u> The Pilot Breathing Almanac (Technical Section 11 of this report) did not exist when F-18 report was written. It is a new tool, and it can be helpful. PBA team encourages USN and USAF to use, and add new data to this database.
6. **<u>2017 Recommendation #6:</u>** Assess the causes of PEs in a systematic way – with sufficient data – with relevant mechanisms
    a. <u>F/A-18 Report Key Finding:</u> A structured data-driven causal analysis effort extending to the organizational level should be launched immediately upon recognition of the existence of both severe and widespread safety hazards.
    b. <u>PBA actions:</u> PBA identified the importance of timing and sequence. PBA collected in-flight data necessary to make a data-driven assessment of pilot breathing system interactions
    c. <u>PBA 2020 assessment:</u> With in-flight measurements and quantitative measurements of breathing system timing and sequence, the causes of PEs can be more precisely identified.
7. **<u>2017 Recommendation #7:</u>** PEs involve many systems and requires expertise in many areas, form a multi-disciplinary team and make sure pilots are included
    a. <u>F/A-18 Report Key Finding:</u> Form a multi-disciplinary working group to conduct a dedicated physiological investigation. The primary focus should be the human physiological basis and root cause, which in turn can drive engineering changes and modifications.

    b. PBA actions: PBA team was multidisciplinary, and the interactions between pilots, data analysts, medical doctors, human factors researchers, and instrumentation SMEs resulted in new insights.
    c. PBA 2020 assessment: Continued support of the idea that small, dedicated, multidisciplinary teams are needed to address PEs. 2020 emphasis is on the pilot – include pilots on your team – listen to all of your pilots.
8. **2017 Recommendation #8:** Develop and maintain a clinical practice guideline
    a. F/A-18 Report Key Finding: A dedicated Clinical Practice Guideline (CPG) for PEs must be developed and implemented.
    b. PBA actions: Spirometry, pulse oximetry, and capnography were major parts of PBA.
    c. PBA 2020 assessment: Continued support of clinical best practices and providing the medical diagnostic infrastructure to collect necessary medical data in a timely way.
9. **2017 Recommendation #9:** Standards should be reviewed and updated where appropriate
    a. F/A-18 Report Key Finding: The U.S. Navy should review:
        i. Standards described in this review, especially the most recent MIL-STD-3050 and determine how those specifications can be incorporated into the current F/A-18
        ii. Workforce capability and billets regarding Human-Systems Integration to determine if they meet the requirements and intent of the applicable sections of DoD Instruction 5000.02
    b. PBA actions: PBA identified issues related to timing and sequence. PBA identified breathing system interactions between pilot breathing, cockpit pressure fluctuations, regulator, and mask components. PBA especially identified a gap in regulator performance specifications – the most difficult and important aspects of regulator performance involve sudden changes and asymmetric breathing patterns. Standards involve constant flow, or sinusoidal waveforms.
    c. PBA 2020 assessment: PBA strongly recommends reviewing and updating standards. Standards related to trumpet curve measurements do not involve timing or sequence. PBA recommends that pilot breathing system standards include specifications of timing and sequence. Hysteresis and Phase Shift are quantitative measures of breathing system timing.

The Navy and the Causes of PEs

Navy data reviewed by NASA in 2017 revealed Hypoxia in approximately 80% of the PE cases examined. Objective data has now given credence to that hypotheses of hypoxia as the root cause. Hypoxia results from the complex systematic breathing dissociations as discussed and demonstrated by PBA. Increased work of breathing is a result of these interactions and not a cause of PEs, but an indicator (symptom) of breathing system erosion on physiological capacity.

Unfortunately, some F/A-18 systems are not designed well enough. Cabin Pressure fluctuations, caused by the F/A-18's ECS, have been shown to cause BSDs. Pilot Regulators adjust to these cabin pressure changes in ways not anticipated by the designers. PBA has shown that the Pilot Masks have major BSD issues.

In the 2017 report, the team concluded that pilot breathing issues are not simply due to differences in individual pilots' susceptibilities, shortcomings in pilot crew equipment, or lack of adequate preparation and training of pilots; rather these issues stem from a basic lack of understanding of human breathing in dynamic flight environments, and the lack of comprehension for the multiple potential complex dynamic behaviors which are possible between the interconnected systems of a modern tactical military aircraft. While addressing flight crew equipment and crew training may help to reduce the rate of PEs, these episodes will certainly never be eliminated without undertaking a fundamental re-evaluation of the institutional establishment of basic requirements and integration for the aircraft life support and pressure control systems. The data collected by the PBA team re-iterates the conclusion that these fundamental behaviors are endemic to the basic design of current fleet aircraft, and that PEs will not and cannot be eliminated without undertaking a fundamental re-think of current established requirements, hardware integration, flight testing, and continued in-flight monitoring of military pilots in real-world field environments.

Examining the Navy's PEs Through Knowledge Gained from PBA

When the NESC started their investigation of PEs for the Navy in 2017, the PE rates from 2007 were continuing to climb, despite the Navy's best efforts to understand their cause and implement corrective actions. Now that the NESC has concluded PBA in 2020, it may be helpful to examine the PE problem from a new perspective and offer opinions about the PE problem in general.

One of the biggest revelations the NESC team came to during the PBA study was that pilot breathing difficulties happened at all. This was surprising for the following reasons:

- PBA was designed to study pilot breathing over a wide variety of flight conditions. It was not designed, nor was it ever expected, that these conditions would ever produce breathing difficulties. (PBA Volume I, Technical Section 1)
- PBA used highly experienced PBA test pilots (PBA Volume I, Technical Section 1) to fly benign flight profiles (PBA Volume I, Technical Section 1) with aircraft that had liquid oxygen (LOX) delivery systems (PBA Volume I, Technical Section 1). As a closed system, LOX provides a more reliable source of oxygen (O_2) at more consistent pressures and flows than OBOGs-equipped jets. In fact, prior to the NESC 2017 investigation, conventional wisdom by many in the flying community was that OBOGS was the root cause of PEs. By flying with LOX-equipped jets, it was assumed that the O_2 delivery system would eliminate most of the confounding effects observed with OBOGS in the F/A-18 study.
- PBA test pilots flew in a non-hostile, less stressful research environment than the typical sorties flown by their Navy and Air Force counterparts.

Despite these more favorable conditions, PBA has proven for the first time, with in-situ data, that in the best of conditions, F/A-18 breathing systems can interact in non-deterministic unpredictable ways (mask – regulators – cabin pressures) and have deleterious effects on breathing.

PBA found that even when a flight is nominal – even when the breathing system is functioning well – even when the pilot reports no perceptible effects, pulse oximetry measurements show that O_2 levels in the pilot's blood are routinely reduced. Hypoxia is defined as reduced O_2 levels in blood and tissues.

Logically, then, if PBA gathered evidence of breathing irregularities and mild hypoxia in benign conditions, using the same masks, with the same regulators, and with a more stable O_2 delivery system than those used in the USN fleet, then PEs have undoubtedly been occurring all along. Fortunately, PBA has evidence that supports this case (PBA Volume I, Technical Sections 6 and 7) and has developed a way forward to diagnose bad breathing aircraft and AFE with the prospect of eliminating them.

Considerations

This section provides reminders to the Navy based on the NESC 2017 F/A-18 assessment and offers updated recommendations based on new experiences and insights developed in PBA.

1. Defining the problem is key to solving the problem

Consider the Oxygen Transport Model first presented in the NESC F/A-18 report (and in PBA Volume I, Technical Section 1) and now revised to include new insights gained from PBA (PBA Volume I, Technical Section 12). It is important to frame the problem as a complex Human System Integration (HSI), identify available evidence, identify missing evidence and fill the gaps with objective scientific data.

2. The approach to the problem is key to solving the problem

NESC team recommended in the F/A-18 report to use a multi-disciplined team, consisting not only of engineers and managers, but also of medical doctors, physiologists, and pilots. PEs occur in the complex human systems interacting with complex aircraft systems. They are governed by principles of engineering systems design interacting in complex ways with human anatomy and physiology.

Throughout the course of PBA, pilot observations were used to guide data analysis. PBA analysts asked pilots about their breathing, and their experiences in the cockpit. PBA medical doctors and physiologist were highly integrated on the team. They listened carefully to what the pilots had to say and worked closely with data analysts to develop a fuller, more complete understanding of the measured data.

Also recommended in 2017 F/A-18 study was to use a structured form of causal analysis to help understand the complex systems interaction problem. Fault tree methods and other linear, progressive techniques can approach the problem using methodologies not well-suited for the PE problem and dismiss possible sources of interacting branches on a fault tree.

3. Focus on flying, not just bench testing

"Fly like you test and test like you fly" is an adage that reinforces the concept that the connection between test and flight goes in both directions. Tests need to be conducted in a flight environment, or the results may not be valid. Operational profiles should be restricted to the envelope where valid test data are available. A pilot breathing system is a complex system, with interactions that only occur in the flight environment.

4. **Use/adapt PBA-developed flight test methods to gather missing data and establish performance baselines**

Profile H - PBA has developed a standardized flight profile, data analysis technique, and database of comparison data to serve as a standard diagnostic flight test (PBA Volume I, Technical Section 10). If the US Navy accepts new aircraft or makes corrective changes to existing aircraft systems, this standard diagnostic test can provide a quantitative way to verify that breathing system performance is healthy. If the US Navy suspects that a specific tail number aircraft has problems, this test can provide a quantitative score to compare one aircraft to fleet-wide standards.

5. **Use/adapt PBA-developed metrics to evaluate the quality of the aircraft/aircrew breathing systems**

PBA can describe the methods to calculate hysteresis, phase shift, and pressure, no-flow (PNF) (PBA Volume I, Technical Section 6). Additionally, PBA can describe ways to calculate an inhalation flow score, and exhalation flow score, an inhalation O_2 score, and an exhalation CO_2 score. (PBA Volume I, Technical Section 10)

6. **Cabin pressure fluctuations are important**

PBA has gained insight about how cabin pressure fluctuations can cause breathing sequence disruptions. Cabin pressure fluctuations can cause the diaphragm muscle movement response to inhalation pressure and flow to become completely negated, or delayed, or amplified. Available data, data analysis techniques, and insights about cabin pressure effects could assist US Navy efforts to identify and correct problems with breathing systems.

7. **Pressure and flow in the O_2 delivery system are important, but the timing of air delivery during breathing (BSDs) is equally important**

Cabin pressure fluctuations can cause breathing sequence disruptions. The changes in lung pressure caused by pilot diaphragm muscle movement are relatively small. In regular breathing in open air, chest cavity expansion/contraction is the only thing causing a pressure difference between lungs and open air. There is a direct correlation between diaphragm muscle movement and inhalation/exhalation flow. In a jet with cabin pressure fluctuations, that direct correlation is lost. The magnitude of cabin pressure fluctuations can be greater than pressure changes caused by diaphragm muscle movement. The effect of diaphragm muscle movement can be completely negated, or delayed, or amplified – by cabin pressure changes. Hysteresis and phase shift provide quantitative ways to measure this effect.

8. **Reconsider the cost/benefit of demand regulators with safety pressure.**

PBA has gained insight about sequence disruptions affecting regulators, and how diluter-demand regulators may be better suited to provide large and sudden demands for air with less delay. Available data, data analysis techniques, and insights about the differences between demand regulators and diluter-demand regulators could assist US Navy efforts to identify and correct problems with breathing systems.

9. Use and continue development of current and new in-flight breathing measurement systems – VigilOX and JPL Mask

Making measurements of pilot breathing in-flight is difficult. PBA has gained a substantial amount of experience (>100 flights) with the VigilOX instrumentation system. The detailed methods and procedures can improve the quality of in-flight data, and can make in-flight testing more consistent.

The JPL – In Mask CO_2 and Water Sensor. The JPL-IMCWS can make fast and accurate measurements inside the mask. AFRC has qualified the sensor as certified flight-test equipment. The JPL – IMCWS has been successfully demonstrated in-flight.

Use of the JPL sensor can be used with mask flow and pressure to isolate the particular valve dysfunctions. If used solely, the JPL may be used as an early warning or as a diagnostic tool for the mask. The new in-mask CO_2 sensor offers significant capability by producing a capnograph with system diagnostic or testing insight. The benefits from having a CO_2 measurement at the mouth and mask exhale valve are substantial. High fidelity data with insight as close to the mouth as possible of pressure, valve function, and CO_2 is a revolution in pilot sensor capability. (PBA Volume I, Technical Section 9)

10. Use/adapt PBA test methods to develop a comprehensive baseline of pilot breathing for a wide variety of conditions (PBA Volume I, Technical Section 11- Almanac)

PBA has developed a database of pilot breathing measurements from >100 scripted flights. Results from US Navy and USAF in-flight testing can be compared to this database.

11. Use/modify our Ground Test Methods to gather missing data

Conducting pre- and post-flight spirometry, capnography, and pulse-oximetry testing was an important part of PBA. If the USN gathers a large volume of data, then effects of flights can accurately assessed with statistical rigor. Even with the relatively small number of PBA flights (compared to USN fleet-wide implementation), pulse oximetry measurements of PBA pilots showed that O_2 levels in the pilot’s blood were routinely reduced.

References

- NESC F/A-18 Final Report, NESC-RP-17-01205, 2017

Appendix 9: Results of Pilot Questionnaires and Interviews

Subjective Pilot Report Questionnaires and Interview Summary

Introduction

Self-report data and techniques

To appropriately examine a phenomenon in the world requires adherence to a set of rules and procedures that help ensure the accuracy and generalizability of the findings. Following standardized research methodology for design, collection, and analysis through a study ensures the accuracy and reliability of the collected data and defines the scope of those findings beyond the study (Jones & Thissen, 2007; Stout 2002). This is easily and readily known for objective or quantitative data, but might seem less well-defined for subjective or qualitative data such as those observed with human subject data. This is not the case. Indeed, these standards must remain extremely strict due to the fluctuations expected due to the natural variance of data within and between humans.

As the name suggests, human subject research examines aspects related to the human. This might include directly measurable components such as those related to the functions within the human body (e.g., heart rate, skin temperature, reaction time) with other objective measurements more useful when derived (e.g., heart rate variability). However, many aspects of human cognition remain impossible to assess with a sensor and instead require the subject to answer a query. This subjective information is incredible valuable and can inform the objective measurements. For example, the General Duty Clause, section 5(a)(1) of the Occupational Safety and Health Act (OSHA), states that employers must provide employees a place of employment that "is free from recognizable hazards that are causing or likely to cause death or serious harm to employees." This is fairly straight-forward for temperature exposures that reliably result in damage and death, however, when it comes to temperature for office workspaces, OSHA can only provide guidance (Lang, 2004). This is due to the high variability of the individual physiological differences and preference. An objective measurement of an 81-degree room temperature with 40% humidity provides information, however, the real question is if these environmental conditions cause an impact to the workforce during task operation. These conditions may be acceptable to some workplace populations and unacceptable to others. If the workplace is peopled with mostly individuals who find this unacceptable then there will be an impact to productivity and job turnover. The only way to know the human perception of the objective information is to ask. The goal is to gain an understanding of this perception with as little error as possible.

The traditional outcome of human interaction examination is to develop probabilistic findings that generalize from a sample to a larger population using empirical evidence rooted in theory. Another outcome can be to simply provide descriptive information about specific individuals in a group. Subjective human cognitive or psychological state data are most frequently assessed with a self-report questionnaire ("on a scale of 1-10 how do you feel?") or structured/unstructured interview ("tell me what happened). This subjective data can be collected either quantitatively through the use of survey scales developed with psychometric methods, or qualitatively via a structured or unstructured interview. The quality and accuracy of these techniques relies heavily on the training and ability of the researcher. A simple word choice can unintentionally produce unusable, misleading, or inaccurate data. In the above example, the employer demands all employees fill out a questionnaire about the temperature of the workplace. The results will go directly to the employer without anonymity. The main question of interest is written as “I produce poor quality work in this temperature environment, and I do not want to come to work.” The employer may have intended to gauge the severity of the temperature impact, but the employee may perceive this to be a threat to his or her continued employment. Next, failing to clearly indicate these responses will be de-identified can provide further cause of concern for an employee in terms of potential future backlash or adverse impact. In this case, an employee may simply not respond but, in this example, the employer made questionnaire completion mandatory. The employer only wanted to make sure everyone filled out the questionnaire, but because poor wording, no concern for privacy, and instituting a mandatory response, an employee might report data that aligns with his or her perception of what might be considered more preferable to the employer, but does not align with his/her actual state. Inaccurate data reduces the ability of the employer to accurately understand areas of concern in the workplace and to enact positive changes to address those issues. Closely adhering to well-defined psychometric principles and techniques can increase response rates and reduce conditions that encourage false data.

The interview is another 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 also requires 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. In the previous workplace temperature example, now the employer uses an unstructured interview style to discuss temperature with each employee. In this case, the employer will not ask the question in the same way to every employee and the employee response will likely be influenced by style of the question, the preexisting interpersonal relationship with the employer, or the power differential. This can produce equally poor results.

Exploring phenomena using established and appropriate scientific procedure can empirically separate fact from fiction by utilizing evidence-based observations designed to falsify or support a theory. The goal of empirical research is to realize understanding through the targeted observation and experience, and analysis. The scientific method is designed to encourage the validity and reliability of those findings in terms of the phenomenon being examined. The scientific method is a multi-stage “procedure starting from observations and description of a phenomenon and progressing over formulation of a hypothesis which explains the phenomenon, designing and conducting experiments to test the hypothesis, analyzing the results, and ending with drawing a conclusion” (Andersen & Hepburn, 2016).

However, in operational environments the traditional scientific method may appear impractical as hypotheses development may be difficult and nearly impossible to statistically test in the early stages. Unclear expectations may yield solutions based on inaccurate assumptions that produce unintended consequences when implemented. Gaining a greater understanding of the depth and breadth of the problem space can provide guidance towards the development of highly controlled studies designed to formally assess variable correlations and to increase the success of those future data collected. This is the case for PBA. This early investigation examines both new objective measurements and subjective measurements to determine lessons learned for future application.

Method. Survey Design, Development, and Interpretation

Prior data regarding physiological episodes (PE) primarily relied on subjective report. The absence of objective measurements of breathing data taken from inside the cockpit and/or breathing loop limited any way to validate the pilot experience. For PE Data, parts A/B/C are data collected primarily through self-report via questionnaire. These physiological event reports consist of an individual's experience and the medical team's perception of symptoms with no objective data collected from within the aircraft. Objective data collected by medical often occurs after lengthy time delay when the situational conditions that lead to cognitive impairment may no longer present. To ensure appropriate interpretations and meaningful conclusions can be drawn from these data, this questionnaire or survey must be psychometrically sound and address features such as dimensionality, reliability and validity (Jones & Thissen, 2007; Stout 2002).

To identify the parameters of a subjective experience, data must be gathered, analyzed, and interpreted. This includes using an accepted metric and method by which to collect those data. A questionnaire is the primary method of measurement for self-report psychological phenomena. These data are subjective as they are based entirely on the individual's perspective. Objective data are those collected using an outside measurement. For example, an individual might subjectively report experiencing symptoms they perceive to be a high fever. The actual state of the body temperature can be measured objectively by way of a temperature measurement. This temperature measurement can confirm or refute the subjective report of high fever which can be used to govern the appropriate mitigation strategy.

A fundamental concept of measurement is that measurement is often imperfect. This imperfection means the observed value reflects some amount of error therefore the true value cannot be not known. The True Score Theory states that the observed value (X) equates to the true value (T) and the addition of an unknown amount of error (e). The goal is to increase the accuracy of the measurement by reducing or explaining the error term. This goes for groups of individuals as well.

Questionnaire development must be appropriately conducted otherwise the data could end up meaningless or uninterpretable. The kind of questions must be appropriate for the desired data such as dichotomous (yes/no), rank order, level of agreement (continuous or likert - strongly agree to strongly disagree), cumulative score, and text box. The wording of the question must be thoughtful and carefully examined to craft questions that help the researcher identify information about the individual taking the questionnaire. Questions that are leading, double-barreled, out of context, confusing, biased, loaded, embarrassing, revealing, or offensive can reduce the accuracy of those data. A leading question is one that suggests an answer more than another. A double-barreled question asks two questions that could have different answers. The appropriate approach to developing questions is to ask subject matter experts such as pilots, flight medical, and first responders to provide questions that help discriminate useful information from non-useful information. After initial development, psychometric testing and analysis should be conducted on a sample to assess if these questions garnered the expected responses and iterate as needed.

Conceptual Reasoning

The pilot is an extremely valuable source of information on the health and safety of the aircraft. Although standardized and objective machine data gathered from an aircraft is desirable for numerous reasons, at this time, the aircraft data cannot provide all information of the subjective experience of the pilot flying the aircraft. The fighter pilot is an expert user and can provide insight into the aircraft in terms of performance changes. Unfortunately, pilot opinion has become less sought.

The NESC team learned that no questionnaires/surveys were conducted with the F/A-18 community with respect to PEs. Interviews with pilots and maintainers, and discussions with USAF scientists indicated that a survey could be very useful in determining the scope of the problem, and the community's main concerns. Such information could help guide the Navy's response to the problem and its communication with the fleet.

Discussions with USAF scientists who participated in the USAF's resolution of the F-22 problems have revealed the importance of Surveys that were conducted in 2011 and 2012.

Surveys afforded a number of benefits to the Air Force:

1. Provided the leadership with:
    a. pilots' views on the F-22 breathing problems
    b. pilots' confidence in the aircraft, and
    c. pilots' views on efforts by the Air Force to correct the breathing problems.
2. Spoke to the rank and file that the leadership had a vested interest in solving the problem
3. Provided important data that became part of the F-22's problem resolution
4. Led to a concerted effort by senior leadership to fix the communication problems

The NESC recommended that a survey be conducted throughout the fleet to capture the overall context of PEs within the envelope of unremarkable flights, as well as to gauge the general attitude regarding the PEs and the Navy's efforts to address them among pilots and maintainers. The information gained from a well conducted survey could help guide the Navy's response to the problem and its communication with the fleet.

PBA Questionnaire and Interview Responses

The subjective query portion of PBA had two main goals. First, to gain insight on the individual differences, experiences, and demographics of the subjects used in this study as they relate to the PBA study variables. Second, as an opportunity to collect information related to previous in-flight experiences from five elite pilots with high expertise, high flight hours, numerous airframe exposures, and extensive training that includes verbalization of experience. These two goals were attempted using a combination of written questionnaire and pseudo-structured post-experiment interview. Recommendations for process improvements follow.

PBA Questionnaire Responses

The questionnaire portion included three parts, each targeting a portion of the reporting that would provide insight into the subjects for the study. The first questionnaire (Pre-Test) involved demographics that would not change frequently such as previous flight experience, airframes, common symptoms experienced as a pilot, PE history, and normal diet and exercise routines. This questionnaire was taken only once. The second questionnaire (Pre-Flight) involved the subjects reporting about factors that change daily and might impact the study variables of interest such as recent altitude exposure, diet, fluid intake, and any current symptoms. This questionnaire was completed prior to each flight. The third questionnaire (Post-Flight) involved the subjects reporting about the experience during flight and any usual events that might impact the collected data.

Pre-Test Questionnaire Summary

The pre-test questionnaire was designed to collect individual differences and demographics of the subjects used in this study and to collect information of previous in-flight experiences. This survey contained questions that pertained specifically to PBA and more general questions related to overall flight history.

Demographics:

The PBA pilots all served in the military, obtained instructor pilot training on one or more airframes, and completed test pilot training. All pilots had prior experience breathing on LOX, some had prior experience with gas oxygen (O_2), and some had prior experience with OBOGS. No pilots reported ever using emergency O_2 in-flight.

Mask wearing:

All pilots reported mask wearing any time in the cockpit except when eating or drinking. Pilots reported the primary reasons for mask removal in a non-heavy aircraft as due to facial discomfort, eating/drinking, difficulty exhaling, scratch/wipe nose, to adjust microphone, Valsalva.

Altimeter:

As reported in the F-18 study, the sole method for a pilot to gather objective information about the cabin altitude is to look at the cabin altimeter gauge absent the use of any wrist-worn altitude display devices. The P/E reporting structure for the USN included a directed question asking for cabin altitude and pilots reported having difficulty reporting the actual value and often reported the expected value based on the flight plan. For PBA, an open-ended question was included to collect individual perceptions related to the usability and readability of the altimeter design and location in the F-18. Comments include:

- Tough to read accurately. Didn't notice issues earlier in my career but now I notice pressure changes a lot more in my ear and on the gauge. When it changes schedule or has an issue, I can feel it my ears before I see something on the gauge...or it alerts me to look at the gauge.
- Some, such as the F-18 and T-38 have cabin altimeters that are out of the pilot's field of view (more difficult to monitor).
- F-18 gauge is in a difficult location. Fighter type aircraft don't display differential pressure.
- They are generally small, difficult to read, and located out of the way such that it is difficult to check quickly and regularly. They don't have aural or illuminated warnings that the cabin altitude is too high. Some of the aircraft would illuminate a Master Caution light and associated Cabin Press light, but these warnings generally come on after the cabin pressure has climbed too high and hypoxia could already be present.

Pressure and Flow:

Pilots reported previously experiencing sensations related to overpressure on a scale ranging from never, one flight, some flights, half the flights, most flights, and every flight. No pilots reported most or every flight for any of the questions provided. All PBA pilots reported having lost cabin pressurization at some point in their flying career.

When flying, have you ever noticed any of these sensations related to overpressure? (Check all that apply)	Never	One flight	Some	Half the flights	Most flights	Every flight
Air forced down your throat	1	0	4	0	0	0
Lungs blow up like a balloon	5	0	0	0	0	0
Lazy breathing (pressure does the work)	3	0	2	0	0	0
Mystery breath (effortless)	5	0	0	0	0	0
High pressure in mask (during inhalation)	0	2	3	0	0	0
Too much flow rate (Emergency oxygen)	5	0	0	0	0	0
Too little flow rate	2	1	2	0	0	0
Air hose vibrating	2	0	2	0	0	0
Airflow stops a little before inhalation complete	3	1	1	0	0	0
Sticky exhalation valve (large initial pressure, then relief)	0	0	4	1	0	0
Backpressure feeling (pressure working against you)	1	1	3	0	0	0

When flying, have you ever noticed any of these sensations related to reduced flow?	Never	One flight	Some	Half the flights	Most flights	Every flight
Breathing through a straw	1	3	1	0	0	0
Sucking rubber in mask	3	1	1	0	0	0
Generating negative pressure in mask	3	1	1	0	0	0
Can’t get enough air/unsatisfactory feeling (slight air hunger)	2	3	0	0	0	0
Labored breathing (extra effort/extra work of breathing)	2	1	2	0	0	0
Cracking the seal to get the flow started	4	1	0	0	0	0
Taking deeper breaths to compensate	3	0	2	0	0	0
Restricted breathing/straining against gear	2	1	2	0	0	0
Too little flow rate	2	2	1	0	0	0
Want to take the mask off to breathe deeper, more freely & fully	1	3	0	1	0	0
Air pressure pulsing slightly (low frequency)	3	0	2	0	0	0
Air suddenly rushing out, speeding up momentarily	5	0	0	0	0	0

Symptomatology and Sensations:

The symptomology questions were based on multiple symptomatology questionnaires used through the USAF, USN, and medical checklists. These were included to examine which wording might garner the best subjective response. Three of five PBA pilots reported previously experiencing air sickness. Three of five PBA pilots reported previously experiencing g-induced loss of consciousness (g-LOC) during flight training.

During or after flying, have you ever noticed any of these sensations? (Please check all that apply)	Never	One flight	Some	Half the flights	Most flights	Every flight
Extraordinary breath holding (3-4 minutes) during ground ops	5	0	0	0	0	0
Tinnitus (ringing ears)	1	0	4	0	0	0
Valsalva overnight / oxygen absorption / ear pain	0	0	4	1	0	0
G-induced Atelectasis (need to re-inflate lungs with cough)	1	1	3	0	0	0
Trachea irritation (Raptor cough)	4	0	1	0	0	0
Lung inflammation / irritation	5	0	0	0	0	0
Slight pain in “lungs” post flight	4	0	1	0	0	0
“Lungs” tired next few days, flat/tortured workouts	4	1	0	0	0	0
Excessive fatigue (asleep before your little kids)	1	2	2	0	0	0

How frequently do you experience the following symptoms after a flight (unrelated to a previous condition)?	Never	One flight	Some	Half the flights	Most flights	Every flight
Ringing in ears	1	1	2	0	0	0
Pressure in ears	0	0	4	0	0	0
Sinus pressure	1	0	3	0	0	0
Headache	1	1	2	0	0	0
Feeling sick to your stomach	4	0	0	0	0	0
Feeling faint	4	0	0	0	0	0
Feeling annoyed or irritated (not attributable to an annoying in-flight event)	3	0	0	0	0	0
Feeling sweaty	2	0	1	1	0	0
Feeling queasy	3	0	1	0	0	0
Feeling lightheaded	4	0	0	0	0	0
Feeling drowsy	1	0	3	0	0	0
Feeling clammy or developing a cold sweat	4	0	0	0	0	0
Feeling disoriented	4	0	0	0	0	0
Feeling nauseated	3	0	1	0	0	0
Feeling dizzy	4	0	0	0	0	0
Feeling as if you are spinning	4	0	0	0	0	0
Feeling as if you would vomit	4	0	0	0	0	0

During or after flight, have you ever noticed any of these sensations? (Check all that apply)	Never	One flight	Some	Half the flights	Most flights	Every flight
Tingling, prickling in extremities	4	0	1	0	0	0
Face tingling, prickling sensation	5	0	0	0	0	0
Ear pain, ear blocks	0	2	3	0	0	0
Pain in fingers, toes, or other joints	5	0	0	0	0	0
Chest pain	5	0	0	0	0	0
Cough	2	0	3	0	0	0
Nausea	4	0	1	0	0	0
Cyanosis/blue coloring of lips or nails	5	0	0	0	0	0
Headache	1	0	4	0	0	0
Sinus squeeze, tooth pain	2	2	1	0	0	0
Abdominal pain	4	0	1	0	0	0
Mental confusion	5	0	0	0	0	0
Disorientation	5	0	0	0	0	0
Vision changes	4	1	0	0	0	0
Lack of focus, difficulty concentrating	5	0	0	0	0	0
Dizziness	5	0	0	0	0	0
Vertigo, tumbling or spinning sensation	5	0	0	0	0	0
Cognitive; struggling with basic tasks	5	0	0	0	0	0
Euphoria	5	0	0	0	0	0
Tired, need to fall asleep	2	0	3	0	0	0
Shortness of breath	5	0	0	0	0	0
Behind the Jet	3	1	1	0	0	0
Feeling "Not Normal"	3	0	1	0	0	0

Hypoxia Symptom Recognition Training:

ROBD has become the standard for Hypoxia Recognition Training across the services. All PBA pilots had hypoxia training in the chamber due to the time period they completed their training. Three PBA pilots also had ROBD training. Two PBA pilots indicated their hypoxia symptoms differed between a hypoxia event in the chamber, the ROBD, and during flight. One pilot reported the same symptoms in both. Another pilot reported the majority of the same symptoms in both with an additional symptom in the ROBD alone. The third pilot reported two symptoms in both and two additional symptoms in the chamber alone.

Which hypoxia symptoms do you feel while in these training settings? (If in both, check both boxes)	In Chamber	ROBD
Shortness of breath / air hunger	2	0
Drowsiness	1	0
Headache	0	0
Euphoria	1	1
Aggression	0	0
Poor judgement	2	0
Incoordination	2	1
Difficulty with simple tasks	4	1
Diminished vision	5	3
Tingling	5	3
Numbness	2	2
Hot/Cold flashes	2	2
Blue nail beds	2	1

Dietary, Hydration, Supplement, and Exercise Habits:

Modified eating habits and tactical dehydration was identified as commonly practiced in the pilot community. Questions were included related to those issues. All PBA pilots indicated some modification to eating habits on days scheduled to fly. Most pilots indicated hydration habits that met and maintained hydration recommendations while some pilots indicated an intentional reduction in liquid to reduce need to urinate in flight. Two pilots reported to regularly bringing water on a flight under two hours, one pilot reported consuming water on a flight less than two hours. Three pilots reporting bringing and consuming water on a flight greater than 2 hours.

Some dietary habits or supplements can influence physiological resilience, so questions related to dietary habits were included. Most PBA pilots reported regular caffeine intake with coffee listed as most frequently consumed, followed by tea. (Note: soft drinks were unintentionally omitted from this list and should be included on future caffeine questionnaires.) No PBA pilots identified following a specific diet plan (e.g., paleo, ketogenic, etc.) beyond low carb/low calorie. Some PBA pilots reported taking supplements such as vitamin C, creatine, protein, and amino acids. PBA Pilots reported approximately 2-5 hours a week of cardiovascular exercise and occasional strenuous exercise within the 2 hours before or following a flight.

Pre-Flight Questionnaire Summary

The second questionnaire (Pre-Flight) involved the subjects reporting about factors that change daily and might impact the study variables of interest such as recent altitude exposure, diet, fluid intake, and any current symptoms. This questionnaire was designed to be completed immediately prior to each flight to determine the baseline for each pilot as comparison for the post-flight survey. Questions included recent altitude exposure (e.g., chamber, flights, scuba diving), food and liquid intake, and fatigue. Data from 82 pre-flight questionnaires have been compiled and examined in aggregate. Pilots were permitted to skip questions, so blank answers were omitted from interpretation as indicated in the question totals.

Pre-Flight Altitude Exposure

Pilots were asked to report any altitude exposure in the 48 hours prior to the test flight. Approximately 79% (65) of the pilots reported no altitude exposure. The 21% (17) of reported altitude exposure was due to flight. A wide range of aircraft and flight profiles were included with a range from high-performance AeroBatics to long-haul extended cruise, with 6 flights being other PBA flights. Altitude exposure details provided the maximum cruise altitude ranged from 6000 ft to FL450. The max cabin altitude range of 6k to 18k. The durations ranged from 30 minutes to 9.8 hours. The time between the previous altitude exposure and PBA test flight ranged from 3.25 hours to 47 hours.

Pre-Flight Diet, Hydration, Exercise, and Sleep

Approximately 95% (78) of the pilots indicated normal eating and hydration habits prior to flight. The 5% (4) of non-normal eating habits was due to a skipped breakfast. All pilots indicated a normal hydration habit. Approximately 85% (69) of the pilots indicated a normal exercise routine prior to flight with the 15% (12) non-normal reports were a reduction in exercise typically related to time constraints.

Approximately 90% (74) of the pilots indicated normal sleeping habits prior to flight with the 10% (8) non-normal responses listed as due to a required shift to a night schedule, an extended period of wakefulness in the night, and an earlier than usual morning wake time. Approximately 16% (13) of the pilots indicated feeling unusually tired or fatigued in the last week. PBA pilots were asked to rate fatigue (weariness, tiredness) by checking the one number that best describes his fatigue on a scale from 0 (no fatigue) to 10 (as bad as you can imagine) at the different time periods ranging from the past week, to the time of the survey. The overall majority of the responses indicated very low fatigue. High fatigue was explained in the comments as due to working long hours temporarily and to multiple time zone changes in the previous few days.

	No Fatigue										As bad as you can imagine
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Please rate your fatigue (weariness, tiredness) by checking the one number that best describes your fatigue right NOW.											
	36%	35%	22%	5%	2%	0%	0%	0%	0%	0%	0%
Total Responses = 81	29	28	18	4	2	0	0	0	0	0	0
Please rate your fatigue (weariness, tiredness) by checking the one number that best describes your USUAL level of fatigue during past 24 hours.											
	11%	48%	27%	9%	5%	1%	0%	0%	0%	0%	0%
Total Responses = 82	9	39	22	7	4	1	0	0	0	0	0
Please rate your fatigue (weariness, tiredness) by circling the one number that best describes your WORST level of fatigue during past 24 hours.											
	2%	10%	43%	22%	14%	1%	6%	1%	0%	0%	0%
Total Responses = 81	2	8	35	18	11	1	5	1	0	0	0

	Does not interfere										Completely Interferes
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Circle the one number that describes how, during the past 24 hours, fatigue has interfered with your:											
A. General Activity	96%	1%	0%	2%	0%	0%	0%	0%	0%	0%	0%
	79	1	0	2	0	0	0	0	0	0	0
B. Mood	91%	4%	1%	2%	0%	1%	0%	0%	0%	0%	0%
	75	3	1	2	0	1	0	0	0	0	0
C. Walking Ability	99%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
	81	0	0	1	0	0	0	0	0	0	0
D. Normal Work (Work outside the home and daily chores)	93%	6%	0%	0%	0%	1%	0%	0%	0%	0%	0%
	76	5	0	0	0	1	0	0	0	0	0
E. Relations with other people	94%	5%	0%	0%	1%	0%	0%	0%	0%	0%	0%
	77	4	0	0	1	0	0	0	0	0	0
F. Enjoyment of Life	93%	6%	0%	0%	0%	1%	0%	0%	0%	0%	0%
	76	5	0	0	0	1	0	0	0	0	0

Total Responses = 82

Pre-Flight Symptom Reporting

A brief symptom questionnaire was included to establish differences in symptoms pre-flight to post-flight. Further reasoning for this metric including the typical pre-flight status for a pilot during normal operation over an extended time window. Similar to the pre-test questionnaire, this symptom list is a composite from commonly used symptom reporting questionnaires. A total of 82 pre-test surveys were at least partially completed. The most reported symptom is slight sleepiness (17), followed by slight muscular fatigue (10). The only symptoms reported as moderate include sleepiness (1), muscular fatigue (1), and vertigo (1).

To what extent are you currently feeling these symptoms?	None	Slight	Moderate	Severe	Total
Low blood sugar	82	0	0	0	82
Cough (not attributable to pre-flight condition)	78	3	0	0	81
Extreme Hunger	82	0	0	0	82
Sleepiness	64	17	1	0	82
Fatigue (muscular)	71	10	1	0	82
Fatigue (mental / cognitive)	77	5	0	0	82
Blurred vision	82	0	0	0	82
Dizziness	82	0	0	0	82
Mood disturbance	82	0	0	0	82
Irritability	81	1	0	0	82
Appearing slowed or "off"	81	1	0	0	82
Light-headedness	82	0	0	0	82
Difficulty breathing	82	0	0	0	82
Anxiousness / Nervousness	82	0	0	0	82
Personality changes	82	0	0	0	82
Appearing euphoric or elated	82	0	0	0	82
Vertigo	81	0	1	0	82
Vision changes	82	0	0	0	82
Disorientation	82	0	0	0	82
Memory difficulties	82	0	0	0	82
Difficulty communicating	82	0	0	0	82
Pain anywhere (e.g., joints)	78	4	0	0	82
Skin rashes	80	2	0	0	82
Nausea	82	0	0	0	82
Dizziness	82	0	0	0	82
Headache	80	2	0	0	82
Clumsiness	82	0	0	0	82
Lack of coordination	82	0	0	0	82
Confusion	82	0	0	0	82
Forgetfulness	82	0	0	0	82
Difficulty Concentrating	82	0	0	0	82

Post-Flight Questionnaire Summary

The third questionnaire (Post-Flight) involved the subjects reporting about factors during flight that might provide subjective insight on the objective data collected during flight. This questionnaire was designed to be completed immediately following each flight. As the pre-flight questionnaire received 82 responses, the post-flight questionnaire received 60. This is due to factors such as a scrubbed flight or the competing schedule demands post-doff. The final observations yield a sample mixture of profiles, pilots, and configurations such that preclude the majority of analyses on the questionnaire data set due to overly sparse, unequal or absent samples, as shown below. The below graph already does not include considerations for seating position, or aircraft model. The remainder of the questionnaire data section will continue with simple data descriptions of the pilot responses

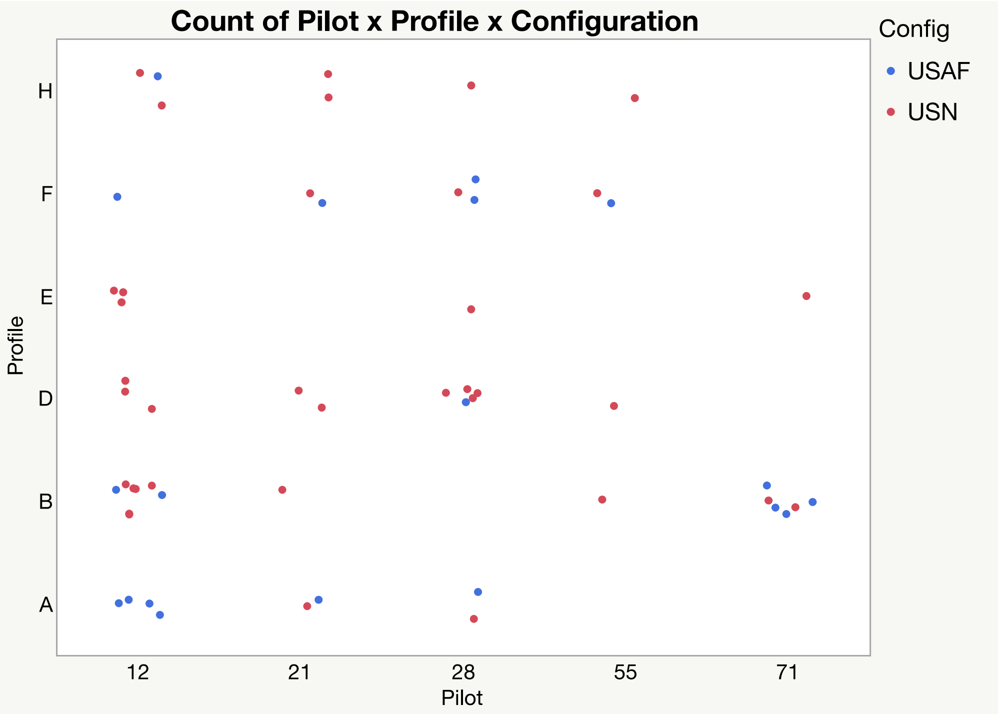

Figure 9.1. Graph of the observation counts for pilot by profile, by crew equipment configuration.

When asked if the flight went as planned, pilots reported “no” for 5 of 53 responses. The comments listed factors related to the aircraft, the mask, and inconsistencies in profile performance due to time pressure. Only three abnormal physical or cognitive experiences were reported. One pilot reported a dull ache in the chest midway through acrobatic performance that was described as the feeling of needing to cough. To elaborate further, this pilot commented being unsurprised of this feeling because this was an elevated G profile, in USN aircrew flight equipment, and on 100% O2 with safety pressure. The pilot stated, “I normally would not notice it except we've been asked to look for small changes with our bodies.” Two reports consisted of the crew stating they were very hot with likely dehydration. Of 58 reported flights, only 6 pilots (10%) brought water with them for the flight and 0 consumed the water during the flight.

All pilots reported wearing the mask the majority of the time in the jet with any removal due to test card directive, to scratch an itch, to wipe away sweat, or discomfort. Of 56 flight observations, the pilots reported 5 (9%) flights as having cabin pressure anomalies. These included intentional RAM DUMP, nominal ECS fluctuations, noticeable ECS surges, inaccurate (low) cabin altimeter, slow cabin pressurization during a Max AB climb, noticeable cabin fluctuations during AeroBatics unrelated to throttle setting.

Comparisons of pre/post flight symptoms

A brief symptom questionnaire was included to examine pre and post flight differences and examine the post-flight experiences for pilots during normal operation over a long-term period. Similar to the pre-test questionnaire, this symptom list is a composite from commonly used symptom reporting questionnaires, please see below. The most reported symptom is pressure in the ears (19 mild, 2 moderate), followed by feeling sweaty (4 mild, 6 moderate, 1 severe), and headache (4 mild). The pilots recorded 15 comments. Pilots expressed the pressure in the ears related to the performance of the flight profiles including “normal” ear pressure during cabin pressure changes and two comments supporting the moderate pain as during combat descent and nose slice maneuvers. Seven comments indicated that that feeling sweaty was due to the temperature both outside and inside the aircraft during flight and expressed the temperature inside the cockpit as problematically high One pilot indicated he had the feeling of slight light-headedness after a sustained 5 G turn with an abrupt roll-out.

Did you feel any of these symptoms today (during or after the flight)?	**None**	**Mild**	**Moderate**	**Severe**	**Total**
Ringing in ears	58	0	0	0	58
Pressure in ears	37	19	2	0	58
Sinus pressure	57	1	0	0	58
Headache	54	4	0	0	58
Feeling sick to your stomach	58	0	0	0	58
Feeling faint	58	0	0	0	58
Feeling annoyed or irritated (not attributable to an annoying in-flight event)	57	1	0	0	58
Feeling sweaty	47	4	6	1	58
Feeling queasy	58	0	0	0	58
Feeling lightheaded	57	1	0	0	58
Feeling drowsy	57	1	0	0	58
Feeling clammy or developing a cold sweat	58	0	0	0	58
Feeling disoriented	58	0	0	0	58
Feeling nauseated	58	0	0	0	58
Feeling dizzy	58	0	0	0	58
Feeling as if you are spinning	58	0	0	0	58
Feeling as if you would vomit	58	0	0	0	58

At the end of the questionnaire, pilots were provided open-response opportunities to comment on breathing experience, symptomology, and any additional thoughts following that specific flight. There were 48 additional comments across 4 open-response questions in 58 completed post-flight questionnaires. The responses were aggregated and analyzed for emergent properties that reveal common themes generalizable to the content area. Here, clusters are conceptual groupings that emerged after the identification of similar statements and the subsequent interpretation of shared characteristics. 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. 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.

The first, and largest, emergent cluster is related to the human breathing system interface in the aircraft and the impact to breathing. One pilot reporting “After flight feels like you can't take as full of a deep breath as before flight.” As this study was known to be an exploration of pilot breathing in flight, it is unsurprising that this cluster contains the most responses. Concerns related to the mask valve malfunction had the most comments of the study with 7 of 58 flights with reported noticeable valve inconsistencies.

- Feeling as if inhalation valve collapses during maximum inhales. No problem during maximum exhale. Happened at all altitudes.
- During maximum inhalation, noticed one of the valves in my mask seemed to collapse, restricting O_2 flow by about 50%. This happened multiple times during Max inhalation both on the ground and in flight. It did not happen during normal breathing or even during "heavy breathing"...only during max inhalation. I didn't experience any symptoms, however.
- After collapsing mask valves on inhalation a few times, Maximum Exhalation also resulted in a collapse or stuck valve reducing exhalation by about 50%. No symptoms as a result, though.
- O_2 mask exhalation valve sticky after max exhale events. Annoying, but not restrictive.
- When I first put my mask up, the inhalation valve seemed to stick a little; it is somewhat common for the exhalation valve to stick but rare that the inhalation valve sticks. This stickiness went away after a few minutes and no additional issues were noted.
- During the Max Inhalation/Normal Exhalation event, on two of three maximum inhalations, it felt as if the valves (2) in my mask collapsed or otherwise partially closed. This slightly restricted the volume of air coming in but did not completely restrict it. Valves immediately opened upon exhalation and worked fine otherwise. Later in the flight during the 'heavy breathing' exercise, I again noticed the valves on my mask appear to collapse or close during max inhalation.
- I experienced periodic breathing "in" stoppages with the mask, regulator, or hoses. I needed to relax for a couple breaths (breathe out) before the O_2 would flow again.

The second most relevant cluster was the subjective experience between the USAF and USN configuration of the flight crew equipment and the non-safety/safety pressure. The majority of the comments that included reference to the fit of the USN AFCE and the USN safety pressure were negative.

- Navy gear makes you feel more restricted, especially when doing spirometry in the cockpit.
- I flew the AF and NAVY configurations back-to-back. I noticed I could "max out" the amount of air provided by the Navy regulator during maximum inhalation events. I could never "max out" the AF regulator (CRU-73.) There was always plenty of airflow no matter how hard I inhaled or exhaled through the CRU-73. On the Navy regulator, if I inhaled extremely hard, I would experience what felt like a hose collapse or momentary valve stick (or regulator running out of air). Max breathing through the Navy system seemed more restrictive than the AF system.
- During the forcible exhales, the mask would inflate like a balloon and if I didn't hold it to my face, the seal around my nose would blow out.

- With the USN gear it required more effort to breathe than with the USAF/NASA gear. Under relaxed breathing the positive pressure assisted inhalation, but exhalation requires some effort against the pressure.
- When exhaling forcefully, the mask filled up as if resisting the airflow. Normal for USN regulator.
- After first High g event (5g) rear pilot asked me how I felt and I said I felt like I needed to cough, so I did. Dry cough probably due to 100% O_2 of the Navy gear.

As noted above, the symptoms questionnaire included a specific query for sweating. Pilots rated sweating highly and provided comments. Here, pilots made simple statements about sweating because of the environmental factor of elevated temperatures rather than an adverse internal reaction to the flight. However, among these comments are several negative references to temperature exposure including indications that the temperature was a detriment to the pilot/mission. Prior interviews with pilots (e.g., PBA, F/A-18, F-35, T6) indicated that operating in a high temperature environment is an incredibly common hazard faced by flight crew. Operational procedures and guidelines exist (such as water intake), but reports of “tactical dehydration” are equally common within the fleet. Heat exposure is a serious hazard resulting in heat related illnesses ranging from simple dehydration to heat stroke and death with compounding effects over multiple events. Hydration level does impact the body’s ability to withstand high performance flight parameters. Furthermore, a pilot who is already borderline dehydrated from tactical dehydration and then exposed to high temperature environment for an extended period of time is unlikely to remain mission ready. Heat should be more consciously considered including the elapsed exposure time and heat accumulation with the appropriate mitigations deployed. Although impossible to remove all heat risk, other strategies should be examined to reduce the risk of thermal dangers prior to and during mission performance. See workplace standards via the Occupational Safety and Health Administration (OSHA) and/or National Institute for Occupational Safety and Health (NIOSH) for further insight (OSHA, 2017).

- The outside temperature during the flight was around 110º F.
- Cockpit was very hot
- With canopy down, sun made the cockpit very hot
- It was hot, especially on the ground with the canopy closed
- Back-seater got pretty sick. I'm not sure the risk of flying demanding maneuvers in an un-air-conditioned cockpit is worth the data. Why don't we limit these flights to cool mornings with OATs < 15 C?
- With no pressurization there is no AC so the plane was hot, especially with the ATAGS G-suit and Navy gear
- During High G portion sweat in my mask caused it to slide down slightly
- Feel slightly dehydrated
- It was hot; I was sweating
- It was hot so I was sweaty.

Another symptom on questionnaire was related to pressure in the ears. Cabin pressure fluctuations in the F/A-18 fleet were commonly reported and could range from very small to very large in magnitude. Elsewhere in this report discusses the importance of small and large oscillations in cabin pressure and the impact on the flight equipment. Here, pilots note being made aware to pressure changes by the ear. This is frequently used as the primary indicator of an unusual change in pressure. A period during operation when a pilot might be performing maneuvers such as these may not benefit from the additional distraction of ear pain or eardrum rupture.

- The pressure in the ears occurred during the nose slice maneuvers.
- Since this flight was entirely below 8000', I did notice the change in pressure in my ears during the mild maneuvers (nose slice). I did not notice it during the more demanding maneuvers like the pop-up attack.
- Felt the pressure change with the pressurization system in my ears.
- My ears will register a cabin pressure change faster than the Cabin altimeter.
- When Cabin pressure changes (flux) you can feel it in your ears first.
- Pain in left ear just prior to level-off on combat descent.
- Normal ear pressure when the Cabin pressure changes.

The next symptom cluster was discussion of G and the new versus the old G-suit. This is an important note as during this study three of the five pilots received new G-suits mid-data collection. These new G-suits were commented both in discussion and in questionnaire comments as a noticeable improvement from the older versions. This is not an ideal occurrence to happen mid-study as a subjectively detectable improvement likely has objective differences. These were not able to be examined in the time allotted.

- Slight light-headedness after a sustained (1-min), 5+ g turn followed by an abrupt roll-out.
- Occasionally needed L-1 for extended G maneuvers
- I have a new ATAGS G-suit which is different than our old G-suits. It seems to function/fit better than the older G-suits and I noticed I didn't really need to strain (L-1) under sustained 5 G like the old G-Suit.
- With new ATSGS G-suit, did not have to strain at all during 5g or other g maneuvers, even to the point where I noticed other things under g that I usually don't. Changed bingo bug while pulling 5g and could feel the weight of my feet on the rudder pedals.

The specialized equipment for use in experimental observation during operation is ideally unobtrusive and unnoticeable. The pilots reported only two instances when the VigilOX was noticeable during the flight performance. Other interviews with the pilots confirmed that the VigilOX did not impede performance, though using the VigilOX itself to gather data was problematic related to difficulty in determining device recording or power status.

- Had a slight mask leak near my nose due to the heaviness of the VigilOX gear. Mask adjusted to full tight.
- The VigilOX O_2 seemed to be twisted causing the hose to rise up blocking my view of the instruments

Post-Test Interview

Ultimately, although valuable, the structured nature of the questionnaire was insufficient to gather more directed and long-form questions related to PBA experience and previous flight experience in general. In human subject research, the interview is a qualitative research method frequently used to collect individual instances of subjective experience. At the end of the experiment, pilots completed a one-on-one debrief to engage in a summary discussion and overall opinion of the entire experiment, profiles, equipment, and perceptions of breathing in flight across numerous air frames. These interviews upheld the aggregate pilot symptom/perception clusters from the questionnaires and provided contexts to better examine and explore the data. In-depth exploration of these data should be conducted in the future.

Future Questionnaire Development

A structured questionnaire was not sufficient for the exploratory nature of this study and the subject population. Although a questionnaire is possible, it must be developed using psychometric standards and practices. For this study, a better alternative would have been an immediate in-person debrief using a semi-structured interview with audio recording for transcription and database entry.

The use of a semi-structured interview would enable expanded pilot commenting and permit follow-up questions related to any potential unexpected events or symptomology that were not previously considered. This method would permit the interviewer (researcher) access to interview techniques such as non-verbal communication and speech patterns to identify lines of questioning that should be worded more clearly or engaged in more directly to generate the best data collection. These data could be used to develop a structured questionnaire for future deployment.

Like the creation of a flight profile to specifically assess the Pilot Breathing System components of an aircraft requires pilot and engineer expertise, the development of a questionnaire to determine the subjective experience of breathing in-flight must be completed using SMEs and formalized psychometrics principles expertise. The goals of an early post-flight interview should be to identify the optimal question and wording to gain the desired information, and to identify the most common statements and responses related to the subjective experience of breathing systems in flight. These are a few thoughts for consideration.

1. During the semi-structured interview, there will be a few structured questions designed to begin the creation of a structured questionnaire.
2. The goal is to iterate and develop these questions to create a formal questionnaire designed to capture the subjective experience of the pilot during the flight to improve the health of the aircraft in the fleet.
3. Successful questionnaire development requires professional expertise in formal psychometric methodology, funding, time, and access to numerous members of the target audience and subject matter experts. Expertise could be available via on-boarding, external contract, or university partnership. This individual or company should have expertise in survey design such as knowledge elicitation and psychometric methodology including factor analysis (exploratory and confirmatory).
4. The resulting questionnaire should have with high sensitivity to detect mild increases in flight symptomology and high discriminability to distinguish among the many potential related causes. For example, pressure fluctuations can be cabin, mask, or line and can have different causes. Factor analysis will permit question improvement, help determine how many factors are present, identify the factors that explain the most variance, identify any needed weighting, and provide a down-selection opportunity to only include as many factors as necessary to understand the data.
5. Target questions should include elicitation of specific observations about their flight, the aircraft, comparisons to other aircraft, or specific segment of the flight. Responses may include a dichotomous response (yes/no) or numeric response (e.g., Likert-Type 1-

7, or scale 1-100) followed by an open-ended response period for the pilot to provide any specific examples or comments. If Likert-Type scales are used, they should have a range of no less than 1-7 to permit more rigorous statistical interpretation.

6. All subjective statements require operationalization. This is the process of defining a nebulous concept variable in terms of a measurable factor. The subjective term "Difficult" needs to be defined into something measurable and so described to ensure equal perspective across subjects. This operationalization will be generated throughout the psychometric questionnaire development process. One method involves the use of SMEs to generate descriptions associated with a term, then another set of SMEs conducting a card-sorting of those previously generated terms to confirm and down-select, and then multiple administrations of the questionnaire with yet another group of SMEs. All, of course, with factor analysis to ensure accurate loading across the expected terms and consistent mapping. For example: what is the subjective performance of the breathing system during flight. Is a breathing system "difficult" or "easy"? Is a 1 like sucking rubber? or filling up like a balloon? Is a 7 like no pressure fluctuations? Or are pilots just conceptualizing "easy" as "normal"?
7. Suggested areas for exploration and required operationalization:
    a. The subjective performance of the breathing system during flight.
    b. The inhalation and ability to easily take in full deep breaths.
    c. The exhalation and ability to fully and easily exhale.
    d. Extent to which the pilot perceived being distraction related to thinking about breathing
    e. Extent to which the pilot was able to focus entirely on the flight
    f. Extent to which any adverse physical or cognitive symptoms or discomfort occur during flight

Near-Miss Data Accumulation

To use data for prediction, the data need to be relevant, reliable, and representative. A major problem surrounding the prediction of PEs is an underreporting of symptoms. The primary goal is the acquisition of a true baseline and accurate trends of minor disruptions before an increase of mission impacts such as a rash of mission aborts. An internal fleet-wide survey has low likelihood of success due to the presence of elements that negatively influence survey response behaviors. A successful implementation has been the inclusion of a neutral third party. Aviation Safety Reporting System (https://asrs.arc.nasa.gov/) is an example of such a strategy. ASRS is a non-jeopardy reporting system for the commercial aviation industry to enable the Federal Aviation Administration to watch for an increase in dangerous trends prior to an aviation incident. ASRS has the capability to conduct specialized surveys to specific focus matters and has for other industries (e.g., rail) and this technique could be implemented to increase pilot participation in reporting and to improve the quality of data and subsequent predictions.

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Appendix 10: PBA Machine Learning

Machine Learning Evaluation Overview

The ability to predict pilot breathing behavior with respect to the many stressors of flight could have implications towards developing hardware and software systems that can help manage those stressors with physiological coping mechanisms. For instance, if it is possible to predict how such factors such as altitude, acceleration, and aircraft orientation affect pilot breathing activity, breathing regulators could be programmed to adapt proactively as soon as the aircraft engages in any complex maneuver. These smart systems would therefore employ the same state of the art computational technology that is integrated throughout autonomous systems applied at the Autonomous Integrated Systems Research Branch and NASA Langley Research Center, the Autonomous Systems Lab at NASA Stennis Space Center, and the Autonomous Systems Project at NASA Ames Research Center, among others. These projects involve using machine learning and artificial intelligence in a variety of applications throughout the mission of NASA where there can be successfully integrated to supplement or enhance human activities or performance.

For the Pilot Breathing Assessment research, an application of artificial intelligence (AI) was developed through advanced machine learning (ML) methodologies to determine if pilot breathing activity could be predicted based on learning from the data collected from the pilot and the aircraft during flight operations. This data driven approach to predictive modeling focused on two flight profiles, one conducted at high altitude and another conducted at low altitude. The resultant mixed dataset allowed the model learn from a diversity of environmental conditions for the aircraft and examine the breathing activities on the pilot in those different environments.

Key Findings:

- Pilot mask pressure can be reliably predicted over 90% of the time
- Peak flow inhalation can be reliably predicted over 85% of the time
- AI can learn from multiple flight profiles and still achieve over 90% accuracy in predictions
- Including USN and USAF aircraft does not decrease model performance; model performance improves with the inclusion of multiple aircraft
- Modeling from multiple pilots is possible with reliable accuracy, albeit lower than the model performance for predicting breathing activity for a single pilot

Data Characteristics and Feature Engineering

Modeling was conducted using a single pilot, and utilized data obtained from flights in a U.S. Navy and U.S. Air Force aircraft, both of which were the F18. Two flight profiles were evaluated, Profile A that was conducted at high altitude, and Profile D that was conducted at low altitude. A summary of the four flights included in this evaluation are as follows:

Flight Number	Profile	Aircraft
50	A (high altitude)	USN
56	A (high altitude)	AF
76	D (low altitude)	AF
83	D (low altitude)	USN

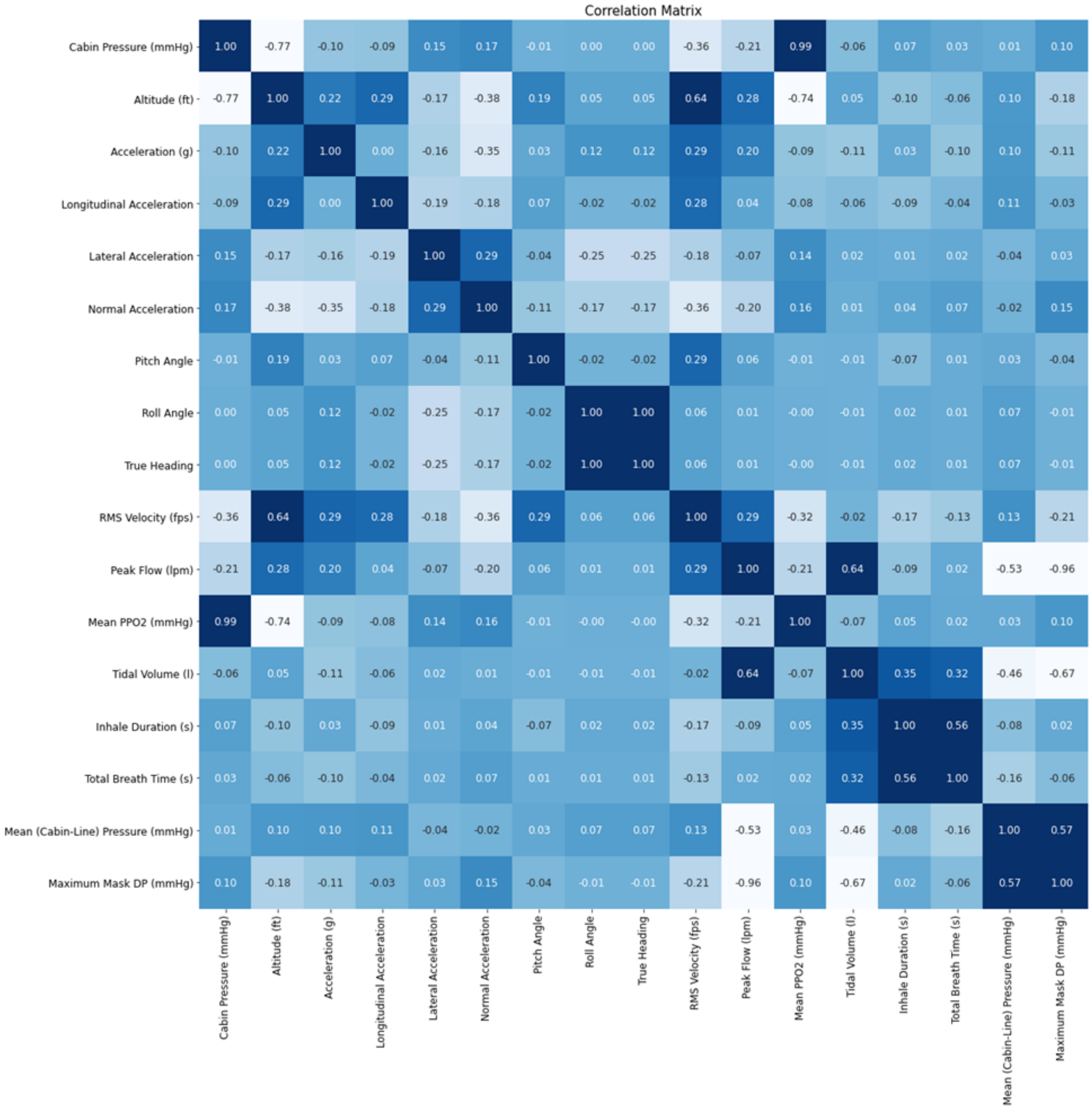
Additionally, three additional datasets were constructed to model data from all pilots who participated in Profile A and D flights: all pilots for Profile A, all pilots for profile D, and all pilots for both Profile A and D together. This included 5 pilots for Profile A and 4 pilots for Profile D.

Flight Number	Profile
26, 27, 39, 55, 56, 61, 85, 85	A (high altitude)
72, 75, 76, 81, 83, 84	D (low altitude)

Data recorded from the above flights included pilot specific and aircraft specific variables, or features, that described the both the pilots breathing activity at each time interval as well as the aircraft's physical and environmental state at that time interval. These data were then subjected to a feature engineering approach whereby there was an aggregation performed across the continuous measurements of pilot breathing to yield the following features:

Cabin Pressure (mmHg)
Altitude (ft)
Acceleration (g)
Longitudinal Acceleration
Lateral Acceleration
Normal Acceleration
Pitch Angle
Roll Angle
True Heading
RMS Velocity (fps)
Peak Flow (lpm)
Mean Pressure O_2 (mmHg)
Mean Cabin Line Pressure (mmHg)
Tidal Volume (l)
Inhale Duration (s)
Total Breath Time (s)
Maximum Mask Pressure (mmHg)

These features were then evaluated for examine any correlations. As seen in the chart below, the correlation coefficient for any combination of two features is rarely above 0.50. This suggests that the data should be modeled with a nonlinear approach.

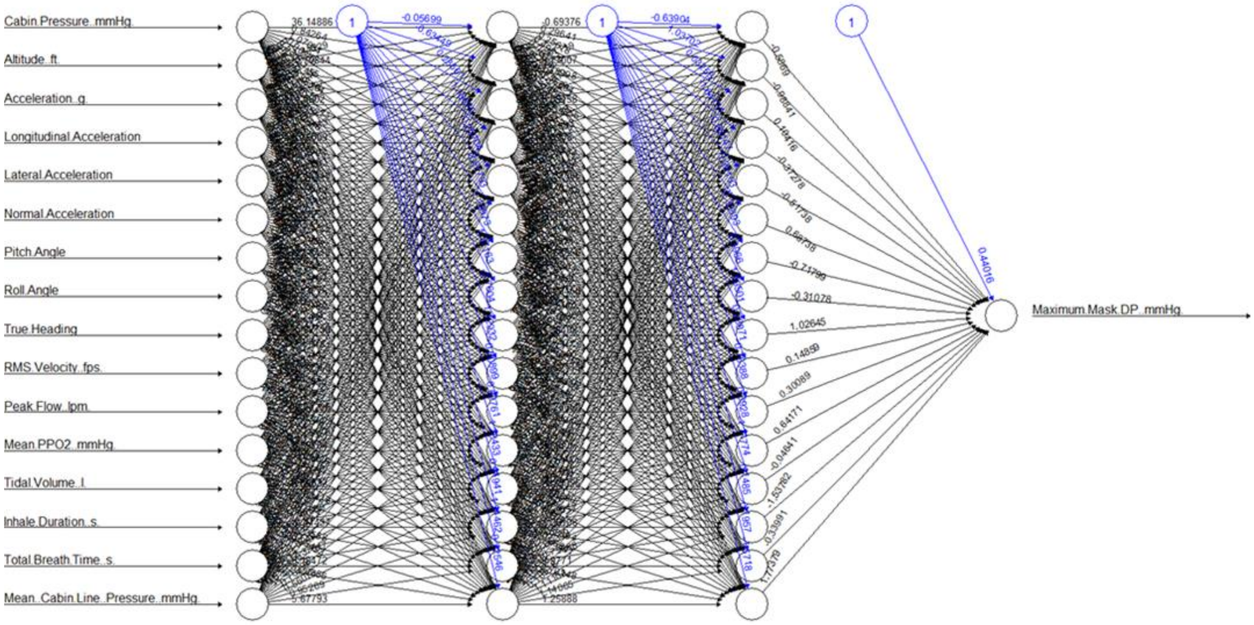


Correlation Matrix

	Cabin Pressure (mmHg)	Altitude (ft)	Acceleration (g)	Longitudinal Acceleration	Lateral Acceleration	Normal Acceleration	Pitch Angle	Roll Angle	True Heading	RMS Velocity (fps)	Peak Flow (lpm)	Mean PPO2 (mmHg)	Tidal Volume (l)	Inhale Duration (s)	Total Breath Time (s)	Mean (Cabin-Line) Pressure (mmHg)	Maximum Mask DP (mmHg)
Cabin Pressure (mmHg)	1.00	-0.77	-0.10	-0.09	0.15	0.17	-0.01	0.00	0.00	-0.36	-0.21	0.99	-0.06	0.07	0.03	0.01	0.10
Altitude (ft)	-0.77	1.00	0.22	0.29	-0.17	-0.38	0.19	0.05	0.05	0.64	0.28	-0.74	0.05	-0.10	-0.06	0.10	-0.18
Acceleration (g)	-0.10	0.22	1.00	0.00	-0.16	-0.35	0.03	0.12	0.12	0.29	0.20	-0.09	-0.11	0.03	-0.10	0.10	-0.11
Longitudinal Acceleration	-0.09	0.29	0.00	1.00	-0.19	-0.18	0.07	-0.02	-0.02	0.28	0.04	-0.08	-0.06	-0.09	-0.04	0.11	-0.03
Lateral Acceleration	0.15	-0.17	-0.16	-0.19	1.00	0.29	-0.04	-0.25	-0.25	-0.18	-0.07	0.14	0.02	0.01	0.02	-0.04	0.03
Normal Acceleration	0.17	-0.38	-0.35	-0.18	0.29	1.00	-0.11	-0.17	-0.17	-0.36	-0.20	0.16	0.01	0.04	0.07	-0.02	0.15
Pitch Angle	-0.01	0.19	0.03	0.07	-0.04	-0.11	1.00	-0.02	-0.02	0.29	0.06	-0.01	-0.01	-0.07	0.01	0.03	-0.04
Roll Angle	0.00	0.05	0.12	-0.02	-0.25	-0.17	-0.02	1.00	1.00	0.06	0.01	-0.00	-0.01	0.02	0.01	0.07	-0.01
True Heading	0.00	0.05	0.12	-0.02	-0.25	-0.17	-0.02	1.00	1.00	0.06	0.01	-0.00	-0.01	0.02	0.01	0.07	-0.01
RMS Velocity (fps)	-0.36	0.64	0.29	0.28	-0.18	-0.36	0.29	0.06	0.06	1.00	0.29	-0.32	-0.02	-0.17	-0.13	0.13	-0.21
Peak Flow (lpm)	-0.21	0.28	0.20	0.04	-0.07	-0.20	0.06	0.01	0.01	0.29	1.00	-0.21	0.64	-0.09	0.02	-0.53	-0.96
Mean PPO2 (mmHg)	0.99	-0.74	-0.09	-0.08	0.14	0.16	-0.01	-0.00	-0.00	-0.32	-0.21	1.00	-0.07	0.05	0.02	0.03	0.10
Tidal Volume (l)	-0.06	0.05	-0.11	-0.06	0.02	0.01	-0.01	-0.01	-0.01	-0.02	0.64	-0.07	1.00	0.35	0.32	-0.46	-0.67
Inhale Duration (s)	0.07	-0.10	0.03	-0.09	0.01	0.04	-0.07	0.02	0.02	-0.17	-0.09	0.05	0.35	1.00	0.56	-0.08	0.02
Total Breath Time (s)	0.03	-0.06	-0.10	-0.04	0.02	0.07	0.01	0.01	0.01	-0.13	0.02	0.02	0.32	0.56	1.00	-0.16	-0.06
Mean (Cabin-Line) Pressure (mmHg)	0.01	0.10	0.10	0.11	-0.04	-0.02	0.03	0.07	0.07	0.13	-0.53	0.03	-0.46	-0.08	-0.16	1.00	0.57
Maximum Mask DP (mmHg)	0.10	-0.18	-0.11	-0.03	0.03	0.15	-0.04	-0.01	-0.01	-0.21	-0.96	0.10	-0.67	0.02	-0.06	0.57	1.00

ML Methodology

Employing ML for predictive studies has the advantage of being able to process large volumes of data to mine for patterns that humans cannot detect. The patterns can represent underlying trends that the AI can discover that may otherwise go unnoticed. For instance, there could be non-linear relationships among the measured variables that could influence the predictive ability of a model (as seen in the correlation matrix chart above). This is often the case with a particular approach to artificial learning, known as the multi-layer perceptron model, also known as a feed forward artificial neural network (ANN). ANNs have an input layer and an output layer, each consisting of a set of nodes. Additionally, there is at least one layer of nodes in between, known as a hidden layer. Initially, each node is assigned a weight value at random. The random model leads to a prediction value, which is then compared to the observed value in the training data. This comparison is made using the error function. Generally, a deep feed-forward (DFF) neural network has many hidden layers in between the input layer and the output, with these layers trained by backpropagation – which is short for “backward propagation of errors”. Additionally the ANN employs a graph-like structure that produces an efficient learning process for the model parameters, as employed with backpropagation. The algorithm uses gradient decent (a first order iterative optimization algorithm that finds the minimum of a function) to calculate the error of the function with respect to the function’s weight, and proceeds backwards through the network from the output back to the input layer. This backwards directionality of the computations for error allows for an efficient calculation of the gradient of each layer, compared to a simpler approach where the gradient of each layer is calculated separately. Using backpropagation as the training algorithm, the activation function for the ANN was logistic regression. The activation function determines the output for each node based on nonlinear mappings from the given inputs.



The ANN model architecture that was used for this analysis is shown below. Two hidden layers were used with 16 nodes in each layer, to match the number of inputs. In the graph below, Maximum Mask Pressure was chosen as the target, however, the same model architecture was used to also model Peak Flow. The values in black represent the inputs going into the next layer, while the values in blue represent the weight for that node.

Each dataset used for modeling was separated into two groups, 80% for training and 20% for a holdout validated set. Each model was therefore trained on 80% of the data and then tested with the remaining 20% (which the model did not evaluate during training) to examine model performance. Each model was run exactly 100 times, and the average model performance value is used in the following discussion.

Results: Single Pilot, Single Flight Profile

The model performance for both Flight A and Flight D data are consistent in terms of predicting Peak Flow and Mask Pressure based on the other measured flight and breathing variables. Initially tested on a single flight, to compare model performance for a USN and AF aircraft, the models show no significant difference in making predictions for either of the two aircrafts. However, when a combined dataset was used that aggregated data from both the USN and AF flights, the model performance improves in a statistically significant way. Mask Pressure and Peak Flow can be reliably predicted with 93.4%, and 75.6% accuracy respectively for the high altitude Profile A, and at 86.3% and 87.4% accuracy respectively for the low altitude Profile D flights. These findings suggest that Mask Pressure is more consistently affected by each of the other aircraft variables. The table below summarizes model performance on each dataset.

Results: Single Pilot, Multiple Flight Profiles

Similar to analyzing the data for single flight profiles, model performance improves when both the USN and AF flights are included. Predicting Peak Flow when both high altitude and low altitude data are included resulted in a higher accuracy than the model performance from the high altitude data at 85.3%. Meanwhile Mask Pressure model performance was improved over both the high altitude and low altitude single datasets at 92.5% accuracy. These findings suggest that more data helps the model learn the latent features from the underlying data better. Additionally, the model is able to discern differences in breathing patterns in the high and low altitude data to therefore adjust the weights for the nodes taking in those inputs to therefore accurately predict what effect the altitude measurement has on the outputs for Mask Pressure and Peak Flow.

Results: Multiple Pilots, Single Flight Profile

Model performance is decreased when including all other pilots in each of the models, while the trend consists for Mask Pressure to be an easier target predictor compared to the Peak Flow. Accuracy for Peak Flow was 71.1% and 70.6% for the high altitude and low altitude flights respectively, while Mask Pressure was at 74.9% and 79.3% respectively. This indicates the there is some ability for the model to learn how to adjust the weights in the hidden layers for individual pilot’s breathing activity – as is necessary to model inputs that vary from person to person given variations in human physiological responses. It is therefore possible that with more data for training this model’s performance could be improved.

Results: Multiple Pilots, Multiple Flight Profiles

Aggregating all pilots who flew a flight for Profile A and/or D into a single dataset, to then use for training the neural network resulted in lower model performance for the targets. Likely due to data imbalances as Profile A had 5 pilots and Profile D had 4 pilots. Additionally, while the volume of data measured during these flights is adequate to train a model to learn one pilot’s breathing activity, to include many pilots likely requires more data than was obtained. However, accuracies at or slightly above 70% indicate the there was enough information in the data to make reliable predictions if given input values to achieve a hypothetical value for Peak Flow or Mask Pressure to generalize to all humans.

Model Accuracy

Flight Profile A	Peak Flow	Mask Pressure
FLT 50 (USN)	70.5%	73.4%
FLT 56 (AF)	77.1%	81.3%
FLT 50 + 56	75.6%	91.3%
Flight Profile D		
FLT 76 (AF)	79.5%	84.6%
FLT 83 (USN)	86.8%	84.9%
FLT 76 + 83	87.4%	86.3%
Flight Profiles A + D		
FLT 50 + 83	78.4%	83.3%
FLT 56 + 76	78.0%	83.0%
FLT 50 + 56 + 76 + 83	85.3%	92.5%
All Pilots		
Profile A	71.1%	74.9%
Profile D	70.6%	79.3%
Profile A + D	69.3%	73.8%

Appendix 11: Glossary of PBA Terms

½ Cuban 8: A Cuban 8 is an aerobatic maneuver in which the aircraft flight path looks like an '8' laying on its side. A ½ Cuban 8 is just the first half of the maneuver.

1-min data: Measurements collapsed into summaries of 1 flight-minute each

20-Hz data-streams: Continuous variables acquired at a rate of 20 points per second

AFRC: Armstrong Flight Research Center (AFRC) at Edwards Air Force Base, CA. All PBA flights were conducted from the NASA AFRC flight line.

Aileron Roll: A low-G aerobatic maneuver in which the pilot pulls the aircraft flight path into a slight climb and then quickly rolls the aircraft around its longitudinal axis.

Aircraft Altitude: Vertical altitude of aircraft as derived from aircraft sensors in feet

Aircraft velocity: Airspeed of aircraft in miles/hour

Aircrew Flight Equipment (AFE): Life support breathing gear (mask, regulator), helmet, harness, parachute, survival kits, etc.

Aircrew Physiologic Monitoring Sensor Suite (AMPSS): System of pilot breathing sensors. According to the developer, Cobham, serves to protect fighter pilots from the effects of unperceivable, debilitating hypoxia like symptoms before they occur.

Airline descent: a gradual descent maintaining a moderate airspeed and moderate power setting, such as might be accomplished by a commercial airliner.

Alignment of data: A crucial aspect of collating multiple data streams into a single larger data set. Usually refers to assigning a common and accurate time base for all data streams.

ALSE: Aircrew Life Support Equipment

Alternobaric Vertigo: Arises from unequal pressure between the two middle ears, usually because the pressures are changing at different rates. Failure to equalize pressure symmetrically can cause the brain to erroneously perceive the difference as movement or spinning.

Anatomical deadspace: Volume of the upper respiratory system that does not participate in alveolar gas exchange

Anoxia: The state in which there is complete deprivation of oxygen supply

Anthropomorphic mannequin: Life sized human figure used for wind blast testing and other gear tests.

Anti-G Straining Maneuver (AGSM): The AGSM involves a forced exhalation against a closed glottis with straining of limb and abdominal muscles just before and during high sustained G's. The exhalation (increased intrathoracic pressure) is maintained for 3-4 sec and is interspersed with rapid inspirations less than 1 sec; the process is repeated cyclically. It is an effective anti-G procedure, increasing the mean-G-tolerance by as much as 4 G. (Bates et al., 1990) [Reference Bates et al., *High G Physiological Protection Training*, AGARDograph No. 322, AMP Working Group 14, AGARD-AG-322, December 1990.]

Arterial Gas Embolization: Occurs when the dissolved gas (mainly nitrogen) comes out of solution and crosses directly into the arterial system

Arterial Spin Labeling (ASL): An analytical method using magnetic resonance imaging (MRI) to quantify cerebral blood perfusion of oxygen.

Average flow volume: The total amount of air entering the pilot's mask in a single flight minute, (liters/min)

Bad actor jet: Pilot term for a particular aircraft that passes all systems tests yet still seems to exhibit more challenges to smooth breathing than other jets of the same type and configuration.

Barodontalgia: Commonly known as tooth squeeze and previously known as aerodontalgia, is a pain in the teeth or jaw caused by a change in ambient pressure

Barosinusitis: A condition manifested by inflammation of one or more of the paranasal sinuses. The inflammation is caused by a pressure gradient, usually negative, between the sinus cavity and the surrounding ambient environment. It can also be caused by large rapid changes in pressure.

Barrel Roll: A low-G aerobatic maneuver in which the aircraft flight path describes a corkscrew, as if rolling around the inside of a barrel.

Breath volume, mean: The average tidal volume within a single flight minute, (liters/breath)

Breath_Vol_mean: Calculated parameter: Average inhaled volume for each breath (liters/breath) calculated by dividing column "mean_FlowLPM_I" by column "Breaths_per_min" for that minute.

Breathing frequency: Number of complete breaths within a single flight minute, (breaths/minute)

Breathing Sequence Disorder: A condition that affects the ability for the pilot to get the proper amount of breathing air at the correct time

Breathing System Disorder: The class of system disorders that can contribute to a PE. Includes breathing sequence disorders, errors in cabin pressure scheduling, insufficient oxygen, rapidly changing levels on oxygen.

Breaths_per_min: Breathing frequency (breath/min) within each individual flight minute, as counted from ISB flow sensor peaks.

Breath-slicing Algorithm: A method developed by PBA for identifying the beginning and end of individual breaths from 20 Hz pressure and flow data streams.

BSD: The acronym of breathing sequence disorder (used many times in the report).

BuNo: Refers to aircraft "build number" indicating age and series of a particular aircraft type, sometimes referred to as CODEX. These are assigned when an aircraft is ordered, not when delivered, so there may be gaps due to contract cancellations. BuNo use is common in contemporary Navy aircraft, but there have been other numbering schemes over the years to differentiate among military aircraft.

Cabin altitude: This parameter is actually expressed as the equivalent cabin pressure as derived from VigilOX ISB sensor, in mmHg.

Cabin Pressure Surges: Rapid changes in cabin pressure control can interfere with proper mask/regulator response from on-demand breathing; these surges can be caused by a variety of factors including rapid ascents or descents coupled with over responsive cabin dump valve.

Cabin Pressurization: Aircraft cabins are pressurized according to a specific schedule related to altitude. At altitude below 8,000 feet, no additional pressurization is applied; in the isobaric region, from 8,000 to 23,000 feet altitude, cabin pressure is maintained at the equivalent of 8,000 feet altitude; above 23,000 feet, cabin pressure is maintained 5 psi above the corresponding external pressure.

Cerebral blood flow (CBF): A measure of the blood supply to the brain in a given period of time. In an adult, CBF is typically 750 ml per minute.

Change Altitude: Change in altitude for each individual flight minute as calculated as max-min value contained within that minute, in feet.

Change cabin alt.: This parameter is actually expressed as the change in equivalent cabin pressure for each individual flight minute as calculated as max-min value contained within that minute, in mmHg.

Check 6 assessment: An event designed for PBA to assess any impact on breathing dynamics when the pilot turns in the cockpit to check for enemy aircraft approaching from behind (as in the 6:00 position on a clock).

Combat Descent: A very rapid descent, such as a tactical aircraft might use to escape or evade enemy aircraft or defenses by quickly descending to low altitude where it would be harder to detect.

Combat Descent: A flight maneuver characterized by a 45-degree descent, dropping 17,000 feet/minute. Has implications on cabin pressure changes.

CRU-103 Breathing Regulator: A particular chest mounted breathing gas regulator used in Navy jets; manufactured by Cobham, Orchard Park, NY. Provides pressure regulated, on-demand breathing gas to the pilot’s mask.

CRU-73 Panel-Mounted Breathing Regulator: A particular panel mounted breathing gas regulator used in Air Force jets; manufactured by Cobham, Orchard Park, NY. Provides pressure regulated, on-demand breathing gas to the pilot’s mask.

Curation of data: A method for evaluating complex data streams; purpose is to detect metadata errors, measurement errors, detector noise, data dropouts, and other disruptions, with the goal of correcting (cleaning) the data based on interpolation or other techniques, or eliminating certain data streams from further consideration.

Dance Card: A specific reference list for the pilot prescribing an order of flight maneuvers representing a particular scripted flight profile

Data Tile Visualization: A data visualization tool developed by PBA in standardized graphs arranged in a 7-tile array. These show a series of pressure and flow breathing interactions with aircraft maneuvers and are used to investigate single minutes of a flight during especially difficult aerobatics flight segments.

Data Visualization: General term for graphical representations of measurements to illustrate patterns and behaviors.

Defog: A feature of the aircraft ECS which blows heated air on the inside of the canopy to eliminate condensation.

Delayed Regulator Response: The regulator requires a pressure signal form the mask to react to on-demand gas flow; for various reasons this signal can be delayed resulting in difficulty in initializing a new breath.

Delta Line Pressure (DLP): A parameter derived from the VigilOX ISB inlet pressure channel calculating the first derivative (slope) of adjacent data points at 20 Hz resolution. Used as a time base alignment marker.

Dependent variables: continuous measurements and calculations of pilot physiological response parameters, including breathing rates, breath volumes, breath flows, breathing pressure, oxygen usage, etc.

DFRL bit: A "self-diagnosis" output from the VigilOX sensor suite data indicating unexpected reverse flow when the differential sensor records a pressure magnitude larger than -10 Pascals.

Differential mask pressure, DMP: A calculated variable based on the difference between the highest and lowest value of mask pressure within a single flight minute, considered to be an indicator of breathing effort, (mmHg)

Diluter demand: An oxygen schedule used in some Air Force configurations wherein cabin air is mixed with mask supply. Represents an effort to reduce oxidative stress at lower altitudes, but 100% oxygen simplifies the implementation of the regulator mechanics.

DMP: Differential mask pressure (mmHg) calculated by subtracting "Min_maskpress" column from "Max_maskpress" columns of original data within each minute.

Effort of breathing: The perceived effort needed to get sufficient ventilation to move gas in and out of the lungs.

Electromagnetic Interference: New flight gear is tested to determine if external electromagnetic fields or pulses could disrupt function.

Event Marker: A tracking system, electronic, audio, or written indicating the start of a new flight maneuver.

Excel: A part of the Microsoft software suite family used for handling and calculating data sets; from Microsoft Corporation, Redmond CA.

Exhalation Valve Lag: A phenomenon sometime referred to as "sticky valve" in that there is a delay for breaking open the exhalation pathway.

Expiration: Alternative word for exhalation

Flight Health Check quad tile: A data visualization tool developed by PBA to show a series of pressure and flow behaviors in standardized graphs arranged in a 4-tile array.

Flight minute: A consecutive designator for the individual minutes constituting an individual flight; a 60 min long flight is broken up into numbered 1, 2, 3... 59, 60 individual flight minutes.

Flight Segment: A subset of a real-world sortie typically defined by a particular maneuver (ascent, descent, high-G turn, etc.), or time spent at a particular altitude or velocity.

FPA: Flight Path Angle – The angle of the aircraft flight path relative to the horizon (positive for a climb and negative for a descent).

G-Breathing: This report uses the term 'G-breathing' to refer to the respiratory aspect of the Anti-G Straining Maneuver (AGSM). The AGSM involves a forced exhalation against a closed glottis with straining of limb and abdominal muscles just before and during high sustained G's. The exhalation (increased intrathoracic pressure) is maintained for 3-4 sec and is interspersed with rapid inspirations less than 1 sec; the process is repeated cyclically. It is an effective anti-G procedure, increasing the mean-G-tolerance by as much as 4 G. (Bates et al., 1990)

G-Exercise: A warm up maneuver used at the beginning of a tactical training sortie to ensure the pilot's G-suit is functioning correctly and to make sure the pilot feels physically ready for elevated-G maneuvering.

G-force vector (G3): Composite G-force vector calculated from VigilOX ISB 3-directional accelerometer in units of G.

G-LOC: G Loss of Consciousness - High load maneuvers cause blood in the body to shift, reducing blood flow to the brain, causing a PE. Less severe cases affect vision and higher order thinking. More severe cases can result in loss of consciousness.

Graphpad Prism: A commercially available statistical software platform that combines scientific graphing, comprehensive curve fitting (nonlinear regression), univariate statistics, and data organization; from GraphPad Software, San Diego, CA.

Group: j^{th} minute within an individual flight

Heat map: Visualization graphics tool using color coded fields indicating numeric values within a rectangular array; for PBA, x-axis (column) is flight minute and the y-axis (row) represents individual flights.

Histogram: A standard statistical visualization graphic showing the frequency distribution of a data set; uses bars of different heights where each bar groups numbers into ranges. Taller bars show that more data falls in that range.

Hyperoxia Priming: Hyperoxia may be defined as the inspiration of supra-physiologic levels of inhaled oxygen such as concentrations of oxygen in excess of ninety per cent. The overall state of hypoxia in aviators experiencing physiologic episodes is paradoxically initiated by the pre-condition of hyperoxia that is established from the moment the pilot begins breathing oxygen concentrations that are in excess of 90%.

Hypoxemia and anoxemia: Refers specifically to states that have low or zero arterial oxygen supply.

Hypoxia Recognition Training: Used to train pilots to recognize early hypoxia symptoms

Hypoxia: Hypoxia is medically defined as deficiency in the amount of oxygen reaching the tissues. Involves four steps: 1) breathing gas delivery system, 2) respiratory system, 3) pulmonic subsystem, and 4) circulatory system

Hysteresis (breathing): Measures the delay in on-demand breathing response due to regulator and mask valve reactions to pressure changes. Early during inhalation demand (mask pressure) exceeds supply (flow);

ILS: Instrument Landing System – A ground-based precision approach capability which provides the pilot lateral and vertical guidance to landing.

Immelman: An aerobatic maneuver in which the pilot executes the first half of a loop, but at the top when the aircraft is inverted, the pilot rolls the aircraft upright and the maneuver is complete.

Independent variables: flight meta-data such as pilot i.d, flight #, aircraft type, tail number, mask configuration, flight profile, etc. plus continuous measurements of aircraft parameters including altitude, speed, acceleration (G-force), cabin pressure, etc.

Inductive Monitoring System (IMS): A NASA machine learning program that detects Mask Pressure-No-Flow (PNF) situations related to disruptions in normal breathing. Occurrence of PNF are indicators of regulator/mask dysfunction.

In-Mask CO_2 and Water Vapor Sensor (IMCWS): Development effort with NASA’s Jet Propulsion Laboratory for in mask sensor suites. Prototype has been successfully flown.

Inspiration: Alternative word for inhalation

instantaneous Delta Mask Pressure (iDMP): A parameter derived from the VigilOX ESB mask pressure channel calculating the first derivative (slope) of adjacent data points at 20 Hz resolution. Used as a time base alignment marker.

Interview Responses: Pilots were interviewed in a casual soon after flights to get more specific information about their physiological and mental status with respect to different flight segments.

Isobaric region: Defined as 8,000 to 23,000 feet altitude; here, cabin pressure is maintained at the equivalent of 8,000 feet altitude.

JPL: NASA’s Jet Propulsion Laboratory is a research and development center in Pasadena CA; collaborating with NESC on in mask sensors.

KCAS: Knots Calibrated AirSpeed – the airspeed displayed to the pilot later during inhalation supply (flow) exceeds demand (mask pressure).

Life Support Systems (LSS) team: Aircrew Flight Equipment (AFE) inspectors, technicians, maintainers, medical officers, engineers, and scientists.

Lognormal distribution: Sometimes referred to as a “multiplicative” distribution, the lognormal frequency distribution is characterized by the geometric mean (GM), and the geometric standard deviation (GSD). It is asymmetric being limited on the left by zero, but may include larger numbers. The defining feature of a lognormally distributed dataset is that it becomes normal (Gaussian) upon log-transformation.

Lognormal transformation: A standard mathematical calculation wherein each individual point within a dataset is replaced by its own natural logarithm. If the original data were lognormally distributed, then the log-transformed data are normally distributed. This a tool for calculating confidence limits.

Low Boom Dive: a maneuver unique to NASA AFRC supersonic research, flown in an F-18 to put a quiet sonic boom on a desired location on the ground. The pilot starts at 49,000’ PA and pulls the aircraft down into a dive to achieve 1.10 Mach in a 53 degree dive at 40,000’. The pilot then pulls 3.5 G to bring the nose back above the horizon and the maneuver is complete.

LOX: Liquid oxygen (LOX) based system. LOX is an earlier technology for providing enriched oxygen for pilot breathing needs; depends literally on the vapor pressure above a liquid oxygen reservoir for breathing. Disadvantage is that it stops working when the LOX reservoir is depleted.

Machine learning: Computer tools used to improve automatically through experience; considered a subset of artificial intelligence programming. Machine learning algorithms build a mathematical model based on sample data, known as "training data", in order to make predictions or decisions without being explicitly programmed to do so when faced with new data.

MadgeTech: An onboard monitoring system for data-logging cabin pressure. Manufactured by MadgeTech, Inc., Warner, NH.

MatLab: A commercially available statistical software suite from MathWorks, Natick, MA.

max_FlowLPM_I: Maximum value measurement from ISB flow sensor for each individual flight minute (liters/min); same as "maximum flow volume".

Maximum flow volume: The highest instantaneous rate of inhalation within a single flight minute, (liters/min)

Maximum power: Full power, including afterburner, on an aircraft engine.

MBU-20/23P oxygen masks: A particular non-rebreathing oxygen mask type manufactured by GenTex, Carbondale PA; used for all PBA flights.

mean_FlowLPM_I: Average measurement from ISB flow sensor values within each individual flight minute (liters/min); same as "Average flow volume**".**

Metadata: Information gathered beyond empirical parameter measurements; refers to fixed flight parameters such as date, time, pilot id, flight number, mask/regulator configuration, aircraft type, tail number, weather, location, etc.

MIL-C-85521 Breathing Standards: Requirements contain a figure of 28.3 cubic feet per hour [=13.35 LPM] of 100% O2 at Sea Level (NTPD), as the baseline to provide each member of the aircrew.

MIL-D-8683C Breathing Standards: Minor change in maximum flow rate per aircrew from 13.12 LPM to 13.35 LPM

Military power: Full, non-afterburning power on an aircraft engine.

MIL-STD-3050: A document with design criteria standards for Aircraft Crew Breathing Systems (published 2015, under revision in 2019). Establishes the minimum design criteria for an aircraft crew breathing system using an On-Board Oxygen Generating System (OBOGS). Prescribes flow rates, volumes, and mask pressure minimums, maximums and swings for given peak flow rates.

Mixed Effects Models: Calculational multivariate models to determine influence of independent variables on pilot breathing response; main feature is the ability to incorporate both continuous parameters (e.g., altitude, cabin pressure, velocity, G-force, etc.) as well as metadata (e.g., pilot i.d., aircraft type, mask configuration, etc.) into a single model. The outcomes are interpreted to assess the influence of independent variables on dependent pilot breathing response variables.

mmHg: Millimeters of mercury; A unit of gas pressure referenced to the pressure exerted by a height of a column of mercury (Hg) in millimeters (mm) at earth normal (1-G) gravity.

Neurologic signs: Due to vascular profusion, reduced brain function due to oxygen reduction can exhibit as a "soft" neurologic sign, such as confusion or a missing or radio calls, rather than a "hard" neurologic deficit such as unilateral paralysis or loss of consciousness.

Normal distribution: Sometimes referred to as the "Gaussian" curve or the "Bell-shaped" curve, the normal frequency distribution is characterized by the mean and the standard deviation of the constituent numbers; it is symmetric about the mean and can include negative numbers.

OBOGS descent: a long, slow, idle power descent. These conditions have reportedly stressed OBOGS breathing systems due to reduced ECS supply air to the OBOGS.

OBOGS: On board oxygen generation system (OBOGS) takes pressurized bleed-air from the jet engine and processes it across adsorbent beds that pass oxygen preferentially. Beds are periodically backflushed to remove residual nitrogen; system is capable of providing close to pure oxygen into a plenum from which pilots breathe. Advantage is that it is unlimited as long as there is fuel for the jet. Disadvantage is that it relies on a stable and clean bleed air supply.

Oxidative Stress: Reactive oxygen species (ROS), commonly called "free radicals", are produced by the human body in the course of normal metabolism by a variety of mechanisms. The term "oxidative stress" describes an imbalance between oxygen free radical formation, and oxygen free radical dissolution through antioxidant repair mechanisms. Hyperoxia is associated with an increased level of reactive oxygen species (ROS).

Oxygen Transport model: Theoretical description of oxygen transport and losses from mask supply to lung to blood to organs (brain). Used to explain different paths along which oxygen could be depleted before reaching vital organs.

Peak Inspiratory Pressure (PIP): A data marker indicating the initial slope of a new breath used for data alignment

Phase Shift: Concept developed for PBA to measure driving pressure and resulting flow temporal disharmony for masked breathing. Describes the mismatch of expected flow and pressure relationship occurring in on-demand breathing.

Physiological episode (PE): An adverse pilot effect from the complex pilot-aircraft interaction that is serious enough to results in an aborted mission; often related to hypoxia or barotrauma.

Physiological Episode Action Team (PEAT): Internal team within US Navy and US Air Force investigating physiological episodes in fighter aircraft; as of Sept. 2018, led by Rear Adm. Fredrick R. "Lucky" Luchtman and Air Force Brig. Gen. Edward L. "Hertz" Vaughan.

Physiological response: Pilot parameters treated as dependent variables within 1-min blocks, such as breaths/min, liters/breath, etc.

Pop Pattern: A training maneuver in which the pilot practices a Pop Up Attack. A Pop Up Attack is used to approach a target area at low altitude to avoid detection by the enemy. The pilot then climbs rapidly to visually locate the target and pulls down into a dive to drop bombs on it before descending back to low altitude to egress the target area.

Positive pressure: Similar to the broader mask "safety pressure" definition, but defined more specifically when comparing the flows, pressures, and timing of on-demand breathing systems that maintain a mask pressure that is greater than cabin pressure.

ppCO$_2$: Partial pressure of carbon dioxide (CO$_2$); parameter indicating the pressure of carbon dioxide in a mixture of gases as if it were alone within that volume.

ppO2: Partial pressure of oxygen (O$_2$); parameter indicating the pressure of oxygen in a mixture of gases as if it were alone within that volume.

Pressure oscillations: Cabin pressure control is not perfect, especially for rapid transition through the isobaric region limits. The pressure system may over- or under-shoot resulting in oscillations.

Pressure-Flow Disharmony: Measured mismatch between the pressure profile and the flow profile, including start/stop and time it takes to reach the peak. Similar to breathing hysteresis.

Pressure-no-flow (PNF): A condition observed during on-demand breathing wherein the subject exerts pulmonary pressure (positive or negative) but the breathing system does not respond with flow. Typically this is very brief, but the occurrences indicate a problem with the regulator/mask configuration.

Proc Mixed: A specific statistical subsystem procedure within the SAS suite designed for mixed effects modeling that incorporates metadata and continuous variables into a single statistical analysis.

Pulmonary function tests (PFT): A systematic set of measurements of the flows and volumes of maximum breath maneuvers designed to assess current human lung performance using medical spirometry equipment.

QQ-plot: Visualization graphics tool using least-squares linear regression to indicate overall data distribution, and to show the position of each measurement within the distribution; for PBA, the x-axis is the calculated z-score for the particular data set, and the y-axis represents the measured value of the measurement. Data are typically log-transformed to achieve coherence with the statistical model as described by a linear plot.

Questionnaires: 6PBA developed detailed questionnaires using numerical scales to assess pilot subjective feelings/attitudes, as well as any experiences with physiological episodes. The purpose was to complement the empirical data and to correlate the subjective with the objective information.

Rad-97: A brand name for a handheld pulse oximetry, CO, and CO_2 monitor from Masimo Corp., Irvine, CA, USA. Used for measuring pre- and post-flight pilot breathing parameters.

Rapid Decompression Compliance: New flight gear is tested to determine if closed and sealed elements might rupture during rapid decompression as in an ejection event.

RCCA: Root Cause Corrective Analysis (RCCA) is a deductive safety engineering method used to analyze a problem, identify its causes and the measures that could be taken to prevent it from occurring again.

Repeat Measures Design: Experimental plan wherein activities are repeated so that “within-subject” variability can be assessed. In PBA, pilots repeated the same flight profiles on different days.

ROBD: Acronym for reduced oxygen breathing device (ROBD) used to train pilots to recognize early hypoxia symptoms

Royal Australian Air Force (RAAF): Aerial warfare branch of the Australian Defence Force (ADF); operates the majority of the ADF's fixed wing aircraft, although both the Australian Army and Royal Australian Navy also operate aircraft in various roles.

RTB: Return To Base

Safety pressure: A general term used to describe the regulator and mask systems that provide breathing gas at a slightly higher pressure than the surrounding environment. Used by Navy to define aid to inhalation during high-G maneuvers and as a protective measure in case of ejection; increases the effort to crack open the exhalation valve in the mask during normal operation. Sometimes used interchangeably with “positive pressure”.

SAS: A commercially available statistical software platform from SAS Institute, Cary, NC; provides a wide suite of statistical analyses; capable of dealing with large data sets.

Scripted Flight Profiles: Predesigned flight maneuvers to test pilot physiological response to specific aircraft parameters including climbs, altitude, g-force, velocity, etc.

SME: Subject matter expert.

SpiroDoc: A brand name for a handheld pulmonary function and testing (PFT) instrument; manufactured by Medical International Research (MIR), New Berlin, WI. Used for measuring pre- and post-flight pilot breathing parameters.

Split-S: an aerobatic maneuver in which the pilot rolls the aircraft inverted and pulls the nose down as in the second half of a loop.

Squirrel Cage: a continuous series of aerobatic maneuvers accomplished without pausing consisting of a loop, a ½ Cuban 8, an Immelman, and a Split-S.

Squirrel Cage: A flight maneuver during aerobatic flight containing three consecutive 10,000 ft span vertical loops. Has implications on cabin pressure changes and g-force.

st. dev. MP: Standard deviation of mask pressure (mmHg) of original data within each minute.

Standard deviation mask pressure, St. dev. MP: A calculated variable based on the standard deviation of the 20-hz data stream captured within each individual flight minute, considered to be an indicator of rapid breathing gas fluctuations, (mmHg)

Standard temperature and pressure (dry) conditions (STPD): Abbreviation indicating that a gas volume has been expressed as if it were at standard temperature (0°C), standard pressure (760 mm Hg absolute), and dry; under these conditions a mole of gas occupies 22.4 L.

Summary Statistics: Tabulated entries for any given data set represented by central tendency (mean, median, geometric mean), spread (standard deviation, range, geometric standard deviation), and confidence limits.

Symptomatology and Sensations: Pilots were asked about short- and long-term symptoms (e.g., disorientation, headache, nausea, cough, and about other sensations e.g., tingling in hands, blurred vision, drowsiness, etc.)).

T-45 Goshawk: A tandem-seat, carrier capable, jet trainer whose mission is to train Navy and Marine Corps pilots.

TACAN: TACtical Air Navigation – a ground based navigation aid used by the US military. Can be used as the source of guidance for an instrument approach to landing.

Tail number: Serves as a “license plate” identifier visible externally that identifies a specific aircraft.

Talking scripts: Standardized cripts normally used in formal testing of communications systems. Adapted for PBA to assess the impact of speaking on pilot breathing dynamics.

Technology Readiness Level (TRL): A numeric designator method for estimating the maturity of *technologies* during the acquisition phase of a program, developed at NASA during the 1970s. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of *technology*.

TM-93-59 SY Breathing Standards: Pilots in fighters may consume considerably more oxygen in excess of 200 LPM per crew member

Trumpet Curve: A data visualization tool relating pressure and flow rate during inhalation and exhalation.

TTC recorders: Flight data instrumentation system from Teletronics Technology Corp, Davidson, North Carolina, USA. Used for datalogging a variety of aircraft parameters including altitude, velocity, and acceleration.

UniqueID: Numbered from 1 to n, representing the n^{th} minute of all PBA flights in sequence for all flight minutes.

USN QIK System: Flight data instrumentation system designed by NAVAIR to record all Mil-STD-1553 Channels; used for datalogging a variety of aircraft parameters including altitude, velocity, and acceleration, plus various communications channels.

Variance components: Estimates of complex datasets that indicate partitioning of variability attributed to individual parameters

Vascular perfusion: The passage of fluid through blood vessels to an organ or a tissue. Perfusion reflects the delivery of essential nutrients (including oxygen) to tissues, and so is directly related to its status.

VigilOX ESB: Exhalation sensor block: Instrumentation for collecting multiple 20-Hz data streams from the interior or from the exhalation port of the pilot's mask. Includes mask pressure, gas flow, temperature, CO_2 concentration, 3-D accelerometer.

VigilOX ISB: Inhalation sensor block: Instrumentation for collecting multiple 20-Hz data between the regulator and the inhalation port of the pilot's mask. Includes inlet flow, inlet pressure, O_2 concentration, 3-D accelerometer.

VigilOX: An onboard monitoring system for measuring pilot related parameters including inhalation flows and pressures, oxygen concentration, cockpit pressure, G-force, as well as exhalation flows and pressures, carbon dioxide and oxygen concentration. Manufactured by Cobham, Orchard Park, NY.

Weight-on-Wheels (WoW): A parameter indicating the ground vs. flight portions of a total sortie; although important for data alignment, this is not routinely logged in F-18 and F-15 aircraft.

Windblast Compliance: Items worn by the pilot need to pass a windblast test before they can be declared airworthy. If there is an ejection seat event, items attached to the pilot's flight suit must maintain integrity. This is a specific test performed by Navy.

Wingover: A low-G aerobatic maneuver in which the pilot slowly pulls the nose of the aircraft up and then slowly rolls to 90 degrees of bank and lets the flight path fall back below the horizon before slowly rolling and pulling back to level flight.

Work-of-breathing: A defined physiological parameter; calculated in terms of the pulmonary pressure exerted multiplied by the change in pulmonary volume, or similarly in terms of the just the oxygen fraction consumption attributable to breathing.

Zoom climb: A rapid climb maneuver in which the pilot does not attempt to maintain a constant airspeed, but instead trades excess airspeed for an increased rate of climb.

z-score: In a normal distribution, z-score is the number of standard deviations an individual point is from the mean. For example, the area in a standard normal distribution curve between z-score = -1.96 to z-score = 1.96 represents 95% of the data.