AFRL-HE-BR-TR-2004-0047

United States Air Force Research Laboratory

PRESSURE BREATHING DURING G WITHOUT A COUNTER-PRESSURE VEST

Major Robert O'Connor
Wayne Isdahl
Paul Werchan

HUMAN EFFECTIVENESS DIRECTORATE
BIOSCIENCES AND PROTECTION DIVISION
AIRCREW PROTECTION BRANCH
2485 GILLINGHAM DRIVE
BROOKS CITY-BASE TX 78235

Ulf Balldin

Wyle Lab
1313 SE Military Drive, Ste 110
San Antonio, TX 78214

May 2004

NOTICES

This report is published in the interest of scientific and technical information exchange and does not constitute approval or disapproval of its ideas or findings.

This report is published as received and has not been edited by the publication staff of the Air Force Research Laboratory.

Using Government drawings, specifications, or other data included in this document for any purpose other than Government-related procurement does not in any way obligate the US Government. The fact that the Government formulated or supplied the drawings, specifications, or other data, does not license the holder or any other person or corporation, or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

//SIGNED//
ROBERT O'CONNOR, MAJ, USAF
Project Scientist

//SIGNED//
F. WESLEY BAUMGARDNER, Ph.D.
Deputy, Biosciences and Protection Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: May 2004

2. REPORT TYPE: Interim

3. DATES COVERED *(From - To)*: 1 Jul 03 – 21 Jan 04

4. TITLE AND SUBTITLE

Pressure Breathing During G Without a Counter-Pressure Vest

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER: 62202F

5d. PROJECT NUMBER: 7757

5e. TASK NUMBER: P8

5f. WORK UNIT NUMBER: 04

6. AUTHOR(S)

O'Connor, Robert; Isdahl, Wayne; Balldin, Ulf; Werchan, Paul

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Human Effectiveness Directorate
Biosciences and Protection Division
Aircrew Protection Branch
2485 Gillingham Drive
Brooks-City Base, TX 78235

Wyle Laboratories
1313 SE Military Drive, Ste 110
San Antonio, TX 78235

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Human Effectiveness Directorate, Biosciences and Protection Division
Aircrew Protection Branch
2485 Gillingham Drive
Brooks-City Base, TX 78235

10. SPONSOR/MONITOR'S ACRONYM(S): AFRL/HE

11. SPONSOR/MONITOR'S REPORT NUMBER(S): AFRL-HE-BR-TR-2004-0047

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release, distribution unlimited.

20040621 027

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report was delivered to Air Combat Command (ACC/DRS) in response to their request for a study of use of the COMBAT EDGE positive pressure breathing (PPB) system without its chest counter-pressure vest. The vest is worn to balance intra-thoracic pressure during PPB, but some aircrew have reported the vest causes increased heat stress and decreased mobility. Eleven subjects, including five F-15 aircrew, completed centrifuge exposures up to +9 Gz using PPB at 60 mm Hg pressure with and without the counter-pressure vest. Additional G-exposures using pressures of 0, 30, and 45 mm Hg were performed without the vest. Elimination of the counter-pressure vest did not significantly reduce G-tolerance. The use of PPB, with or without the vest, was preferred by all test subjects. PPB at 60 mm Hg produced the highest G-protection and was preferred by the test subjects over lesser pressures. Subjects reported no adverse effects from use of PPB without chest counter-pressure. Whether PPB without counter-pressure will increase fatigue during multiple sorties was not determined.

15. SUBJECT TERMS

COMBAT EDGE, positive pressure breathing, chest counter-pressure vest, acceleration tolerance

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified	33	Maj. Robert O'Connor
					19b. TELEPHONE NUMBER *(include area code)* (210) 536-3849

Table of Contents

Figures

Tables

1.0 SUMMARY: Pressure Breathing During G Without a Counter-Pressure Vest

Purpose: This study was to determine whether safe and adequate G-protection could be maintained if the COMBAT EDGE counter-pressure vest were eliminated.

Method: Eleven subjects, including five F-15 aircrew, completed centrifuge exposures up to +9 Gz using pressure breathing for G (PBG) at 60 mm Hg pressure with and without the counter-pressure vest. Additional G-exposures using pressures of 0, 30, and 45 mm Hg were performed without the vest.

Results/Discussion: Elimination of the COMBAT EDGE counter-pressure vest did not significantly reduce G-tolerance. The use of PPG, with or without the vest, was preferred by all test subjects. PBG at 60 mm Hg produced the highest G-protection and was preferred by the test subjects over lesser pressures. Subjects reported no adverse effects from use of PPG without chest counter-pressure. Whether PBG without counter-pressure will increase fatigue during multiple sorties was not determined.

Recommendations:

1) Continue to use PBG at pressures delivered by COMBAT EDGE
2) Conduct an operational test to determine the in-flight safety and utility of COMBAT EDGE without the counter-pressure vest

If flight test results are consistent with vest elimination:

1) Aircrew should wear the counter-pressure vest for altitude protection on flights at or above 45,000 ft in the F/A-22
2) COMBAT EDGE relief valve (CRU-94/P ITB) must be modified
3) Perform a safety review of the COMBAT EDGE oxygen regulator

2.0 BACKGROUND:

2.1 The Combined Advanced Technology Enhanced Design G Ensemble (COMBAT EDGE) evolved from the advanced development program known as the Tactical Life Support System (TLSS). Along with other protective features, TLSS utilized positive pressure breathing (PPB), a chest counter-pressure vest, and a full-coverage anti-G suit to provide altitude protection to 60,000 feet and sustained acceleration protection to +9 Gz. The COMBAT EDGE (CE) program was initiated to allow for rapid fielding of the G-protective aspects of TLSS. As part of the rapid fielding process, the developmental full-coverage G-suit of TLSS was replaced with the legacy CSU-13B/P G-suit. The vest was retained for G-protection because studies had shown that G-endurance increased when PPB was used with chest counter-pressure.

2.2 The purpose of the CE system was to reduce the physical workload of aircrew performing the anti-G straining maneuver (AGSM). When done correctly, the AGSM is a total body effort, combining a strong contraction of the muscles of the limbs, stomach and chest with a breathing pattern that requires a rapid and forceful exhalation and inhalation every three seconds. While a proper AGSM can effectively increase G-tolerance, the muscular strain component is extremely fatiguing and the breathing component is hindered at high +Gz by the increased downward force on the chest wall. CE uses positive pressure breathing for G (PBG) to increase intra-thoracic pressure and facilitate inspiration during +Gz exposure. The increase in intra-thoracic pressure elevates blood pressure and results in a reduced muscular straining requirement during the AGSM. The enhanced inspiration from PBG supports air exchange at high-G.

2.3 The PBG delivery schedule of CE begins at +4 Gz and increases by 12 millimeters of mercury (mm Hg) of pressure per G to a maximum of 60 mm Hg at +9 Gz. The CE components worn by aircrew consist of the following:

Modified HGU-55/P Helmet
MBU-20/P Oxygen Mask
CRU-94/P Integrated Terminal Block (ITB)
CSU-13B/P Anti-G Suit
CSU-17/P Counter-pressure Vest.

2.4 The counter-pressure vest (see Appendix, Figure 1) is worn to balance the intra-thoracic pressure during PBG and to reduce the respiratory fatigue and discomfort associated with active exhalation against the high breathing pressures. While CE helps to reduce the risk of high-G exposure, a number of aircrew have stated a concern that the vest adds to their heat stress during flight, and may create a burden that is greater than the benefit provided by PBG. At the request of Air Combat Command (ACC), the Air Force Research Laboratory's (AFRL) Biosciences and Protection Division (HEP) conducted a study of the heat stress associated with wear of the vest (Balldin et. al., 2002). It was determined there were no significant differences in core or skin temperatures, or levels of dehydration, with or without wear of the vest. Nevertheless, to ensure aircrew do not unnecessarily endure a possible in-flight discomfort or distraction, ACC requested that

AFRL/HEP determine if PBG can be successfully utilized without wear of a counter-pressure vest (ACC/DRS letter dated 27 Mar 03). Specifically, the Commander of ACC requested that the following be addressed:

> "Review the requirement for positive pressure breathing (PPB) and an upper counter pressure vest. Evaluate different levels of PPB without the chest counter pressure garment. Determine the optimal level of PPB and G protection without the upper counter pressure vest. Report the marginal G benefit with and without the upper counter pressure vest."

2.5 Several studies have shown that PBG increases G-tolerance and endurance (e.g. Burns and Balldin, 1988; Morgan et, al. 1992; and Tong et, al. 1998). As mentioned above, one of the benefits of PBG is the reduced requirement for muscular strain during the AGSM. In a recent study by Fernandes et. al. (2003), high muscle activity was observed far less during PBG than without PBG. However, it is not known if use of PBG without chest counter-pressure, referred to as unassisted PBG, will increase the work of respiratory muscles to the point of discomfort or decreased G-tolerance. In an abstract by Gronkvist et. al. (2003), it was shown that use of a counter-pressure vest during PBG reduces the breathing effort, suggesting removal of the vest increases work during expiration even at high-G.

2.6 In order to successfully use unassisted PBG, the elimination of the vest must not decrease G-tolerance or endurance, increase aircrew discomfort or fatigue, or produce a medical risk for aircrew. The primary medical concern related to unassisted PBG is the potential for over-distension of the chest and lungs, with the possible result of a tearing of the lungs. Earlier studies using high levels of unassisted pressure breathing at 1 G did not show such effects. Meehan (1966) had five subjects exposed to 30 minutes of 60 mm Hg pressure breathing in the supine position four times a day for 28 days in a bed-rest study without a counter-pressure vest or anti-G suit. Balldin and Wranne (1980) exposed subjects to unassisted pressure breathing at 50 mm Hg for 4 minutes with an anti-G suit and with catheters in the right atrium and in the pulmonary artery for hemodynamic measurements. Neither study showed any adverse effects other than breathing fatigue. In a report by Krebs and Pilmanis (1996), evidence is presented suggesting the unsupported chest wall of the human population can safely support 80 mm Hg static and dynamic over-pressure of the lungs. This would be similar to unassisted PBG during a G-induced loss of consciousness (G-LOC), when there is no counter-pressure support to the thorax since the breathing muscles are relaxed. Krebs and Pilmanis also state that safe static pressure in the human population, wearing chest and abdomen support devices, is at least 190 mm Hg. That pressure is similar to what can occur during the respiratory straining portion of the AGSM, during weight lifting, and during the playing of musical instruments (such as the trumpet), when the breathing muscles restrict over-expansion of the lungs. Fortunately, the highest PBG pressures are provided at the highest G-levels. During high-G exposure, the increased weight of both the thorax wall and the aircrew's flight equipment will create some counter-pressure to the thorax, and thus may permit use of unassisted PBG up to 60 mm Hg.

2.7 Centrifuge studies of unassisted PBG to date have used a maximum of 52 mm Hg of breathing pressure, and have used a maximum G-onset rate of +1 Gz per second. One study reported increased respiratory fatigue with use of breathing pressure above 30 mm Hg (Shaffstall and Burton, 1979). However, the extended duration of the G-profile used in that study may not be operationally relevant. Most recently the Swedish Defence Research Agency reported on a centrifuge study (0.5 G/sec onset rate) comparing use of inflated and non-inflated counter-pressure vests with 40 mm Hg PBG (Gronkvist et al. 2003). They demonstrated no change in G-tolerance to +8 Gz between the vest/no vest (non-inflated) conditions, but confirmed the earlier finding of increased expiratory work of breathing without wearing of a vest. The purpose of this study was to determine whether unassisted PBG, with up to 60 mm Hg of breathing pressure, is acceptable for use during 6G per second onset exposures up to +9 Gz.

3.0 METHODS:

3.1 **Subjects**: Eleven volunteer subjects (nine males and two females) started and completed the study. The mean age of the subjects was 32 years (range 24-42), mean height was 69 inches (range 65-73), and mean body weight was 166 lbs. (range 128-210).

3.2 Five of the subjects (four males and one female) were aircrew currently flying high-performance aircraft. Four of those five were F-15C pilots, and the fifth was an F-15E weapons system officer. Three of the aircrew had over 1000 flight hours in their current aircraft, a fourth had over 500 hours, and the fifth had less than 500 total flying hours.

3.3 The remaining six subjects were members of the AFRL/HEPG (Aircrew Protection Branch) acceleration subject panel. All were experienced with the use of CE, and had demonstrated the ability to pass AFI 11-404 centrifuge qualification requirements for F-15 aircrew.

3.4 **Test Conditions**: Each subject completed the following five test conditions:

I. No PBG
II. Unassisted PBG up to 30 mm Hg at +9 Gz
III. Unassisted PBG up to 45 mm Hg at +9 Gz
IV. <u>Assisted</u> (with a vest) PBG up to 60 mm Hg at +9 Gz
V. Unassisted PBG up to 60 mm Hg at +9 Gz.

3.5 Each condition was completed on a separate day, with at least 22 hours between tests. The order of presentation of the five conditions was not randomized among the subjects. Each subject was exposed to the conditions in the order shown above. The logic for this approach was twofold: 1) we did not want to expose subjects to high breathing pressures during unassisted PBG if they had discomfort or difficulty at lower pressures; and 2) if there was a learning or acclimation effect, we wanted to give unassisted PBG at 60 mm Hg its best chance of succeeding, since that pressure would perhaps be the most protective for aircrew, and any required change of the existing PBG delivery schedule would necessitate a change of the PBG output of the current CE aircrew breathing regulators.

3.6 **Centrifuge G-profiles**: For all test conditions, the following G-profiles were used to determine subject tolerance to gradual and rapid G-onset, both with and without use of the AGSM. The G-suit was worn for all profiles, and was inflated according to the standard inflation schedule. The G-profiles were conducted in the order listed below.

3.7 Relaxed gradual onset (0.1 G/second) run (GOR) to +9 Gz. The subjects were instructed to remain as relaxed as possible until experiencing 100% peripheral light loss (PLL) or 50% central light loss (CLL), as determined by viewing peripheral lights at a 60° angle from centerline and a central light. At that point, they were to begin their AGSM. The exposure continued until they once again experienced 100% PLL or 50% CLL, the centrifuge reached +9 Gz, or they stopped due to fatigue or discomfort. For conditions II-V, the subjects were permitted to contract their chest and stomach muscles as needed to control their breathing volume and chest expansion when the PBG reached high levels.

3.8 After a 5-minute rest period, a series of relaxed rapid onset (6 G/second) runs (ROR) were started at +4 Gz, and increased by +1 Gz per run, to a maximum of +9 Gz. Each G-exposure lasted 15 seconds, or until the subject reached the vision end point criteria of 100% PLL or 50% CLL. Subjects were again permitted to contract their chest and stomach muscles as needed to control chest inflation due to PBG; however, they were instructed not to use an AGSM. The subjects had a 2-minute rest period between exposures. After each ROR, subjects were asked to estimate their overall discomfort level during the G-exposure by using the following scale (modified from the Borg scale developed for perceived exertion).

0	**Nothing at all**
0.5	**Very, very weak (just noticeable)**
1	**Very weak**
2	**Weak (light)**
3	**Moderate**
4	**Somewhat strong**
5	**Strong**
6	
7	**Very strong**
8	
9	
10	**Very, very strong (almost max)**
11	**Maximal**

3.9 The next series of centrifuge runs consisted of 15-second ROR exposures with the subjects performing an AGSM throughout each exposure. The series began at whatever G-level the subject was not able to complete during the previous relaxed ROR exposures. For example, if on the relaxed ROR series the subject reached vision end point criteria 8 seconds into the 15-second +6 Gz exposure, the ROR with AGSM series would start at +6 Gz. The ROR with AGSM series increased by +1 Gz per run. The end point criteria for this series were again 100% PLL, 50% CLL, completion of the +9 Gz run, or the subject stopping due to fatigue or discomfort. After each run the subjects were asked to estimate their level of discomfort, and to use the same scale to estimate the amount of effort they had to exert with their AGSM. The subjects were given a 10-minute rest period after completing this series.

3.10 The last G-profile was a closed-loop simulated air combat maneuver (SACM), and was intended to provide a limited assessment of G-endurance with use of PBG with and without chest counter-pressure. Closed-loop means that each subject controlled his/her actual amount of G-exposure. A target-tracking task was displayed on a flat-panel screen mounted at eye-level within the centrifuge gondola (see Appendix, Figure 2). During the task, the subjects used a force stick with their right hand to attempt to maintain a cross-hair over a moving target. If the subject stayed directly on target, he/she would experience continuous 10-second rapid-onset exposures alternating between +5 and +9 Gz until a total of four 10-second periods at 9 G and five 10-second periods at 5 G were completed. The subjects were instructed to finish the entire SACM. Thus, if they began to approach light-loss criteria during any 10-second period, they were instructed to reduce pressure on the force stick until the Gs decreased to the point that their vision returned and they were able to continue. They were instructed not to rest during one period in order to do well on a subsequent period. Rather, they were asked to maintain their maximum performance throughout the SACM, decreasing the Gs only as needed to avoid a G-LOC or stopping early due to fatigue. After the SACM, and all other G-exposures, the subjects were asked to comment on the suitability of the amount of PBG for each G-level, any discomfort from the PBG, the degree of effort required to control their inhalation or initiate exhalation, or any other point they wished to make.

3.11 **Control of PBG Delivery**: An ALAR high-flow anti-G valve and CRU-93/A breathing regulator were used for all centrifuge exposures. The inlet gas to the breathing regulator was compressed air. In an aircraft, the PBG output of the CRU-93/A is determined by a pneumatic signal from the anti-G valve. When the aircraft undergoes an increase in G, the G-valve begins to fill the G-suit. When +4 Gz is reached, the signal from the G-valve to the CRU-93/A causes delivery of PBG to begin. In the centrifuge, a sense line connected the G-valve to the CRU-93/A, with a back-pressure regulator and a flow-limiting valve placed midway along the sense line. The back-pressure regulator functioned similarly to a relief valve by relieving to ambient any pressure exceeding its set pressure. The flow-limiting valve was installed to prevent the back-pressure regulator from affecting the G-suit pressure. During Condition I exposures, the CRU-93/A was placed in the ON mode (no PBG), and the back-pressure regulator was set to relieve at 15 psig. For Conditions IV and V the back-pressure regulator was again set to relieve at 15 psig, but the regulator was placed in PBG mode and allowed to deliver PBG according to its normal schedule. For conditions II and III, the back-pressure regulator was set to relieve at 7.25 psig and 9.13 psig to restrict the signal to the breathing regulator, such that PBG was limited to a maximum of 30 mm Hg and 45 mm Hg, respectively. Up to those points, the CRU-93/A delivered PBG in a normal fashion, but when those pressures were reached the restricted input from the G-valve prevented further increases in PBG even though the +Gz levels and the delivery of pressure to the G-suit were increasing.

3.12 **Instrumentation**: The subjects wore sternal and biaxillary electrocardiogram (ECG) electrodes to allow for calculation of heart rate (heart rhythm was also monitored for HEPG subject panel members only). Other variables monitored were mask cavity pressure (panel subjects only), inspiratory flow, breathing regulator outlet pressure, G-suit inlet pressure, and G level. Mask cavity pressure was not measured for the aircrew because they wore their own MBU-20/P oxygen masks and it was not possible to instrument the masks with the necessary pressure tap. Nevertheless, the regulator outlet pressure and inspiratory flow recordings permitted necessary tracking of mask leaks or changes in breathing pressure.

3.13 **Test Procedures**: After attaching the ECG electrodes, the subjects donned the following equipment: CWU-27/P Aircrew Coverall (flight suit), Flight Boots, CSU-17/P Counter-pressure Vest (Condition IV only), CSU-13B/P Anti-G Suit, PCU-15A/P or PCU-16 A/P Parachute Harness (without the LPU-9/P Life Preserver attached), CRU-94/P Integrated Terminal Block, Modified HGU-55/P Helmet, and MBU-20/P Oxygen Mask. A survival vest and life preserver were not used in order to reduce the weight of equipment overlaying the chest and abdomen. This was meant to represent a worst-case scenario in terms of least amount of chest counter-pressure when PBG was delivered at high-G. For conditions II, III, and V the vest attachment port of the CRU-94/P ITB was plugged (see Appendix, Figure 3). This was to prevent leakage of breathing gas through the ITB relief valve. That valve is exposed when the vest is not attached, and will open when the pressure of breathing gas inside the CRU-94/P exceeds approximately 38 mm Hg.

3.14 After dressing, the subjects' mask fit and intercom were evaluated using a TTU-529/E Pressure Breathing Oxygen Flight Ensemble Test Set. The test required the subjects breathe a pressure of 30 mm Hg to check their masks for leaks.

3.15 The subjects then moved to the centrifuge gondola and strapped into the seat. The seat was in the upright position, equivalent to the 13-degree seat-back angle in the F-15. The subjects had an electronic hand-held centrifuge brake that they held in their left hand during all runs except the SACM. They were instructed to release the brake according to the light loss criteria, or anytime they wanted to stop an exposure due to fatigue or discomfort. During the SACM, the subjects could stop the exposure by releasing the force stick used for closed-loop control of the centrifuge.

3.16 Before starting the G-exposures, the subjects completed a 1G practice session of the target tracking task. They also completed another practice session of the task during the 10-minute rest period prior to the SACM.

3.17 **Statistical Analysis**: For the GOR and ROR relaxed and straining profiles, a repeated measures analysis of variance (ANOVA) was performed on each outcome measure to test for general differences among the five experimental conditions. When significance was found, post-hoc simple effects tests (paired t-tests) were conducted to identify specific differences among the five conditions. For the SACM profile, G-dose and RMS outcome measures (see paragraphs 4.6 and 4.7) were each analyzed, separately, using a repeated measures ANOVA that tested for differences among the five experimental conditions across the four peaks of the SACM. If significant condition or condition by peak interactions were detected, post-hoc tests were performed at each peak, separately, to isolate specific differences among the 5 conditions. Finally, for the physiologic and subjective measures (i.e., heart rate, effort and discomfort), Student's paired t-tests were used to compare the vest and no-vest conditions. Based on a statistical power analysis for the post-hoc comparisons, we determined that a sample of 11 participants would provide an 87% chance (power = 0.87) of detecting a difference of one standard deviation of the difference in magnitude (effect size = 1.0) when testing at the two-tailed 0.05 alpha level.

4.0 RESULTS:

4.1 Table 1 shows the mean G-level obtained by the 11 subjects during the relaxed portion of the GOR exposures (individual results for each subject are provided in the Appendix – Table 8). The overall results are higher than would normally occur during relaxed runs due to the inflation of the G-suit and the use of PBG. There was no significant difference in G-level between Conditions III, IV, and V. However, the G-levels for all three of those conditions were significantly greater than those for Condition I ($p<0.001$) and Condition II ($p<0.02$).

Table 1. Mean G-level Obtained During Relaxed Portion of the GOR

Condition	Amount of PBG and Vest Status	G-level Obtained
I	No PBG	6.7 G (±1.1)
II	30 mm Hg PBG w/o vest	7.1 G (±1.7)
III	45 mm Hg PBG w/o vest	8.0 G (±1.0)
IV	60 mm Hg PBG with vest	8.2 G (±0.9)
V	60 mm Hg PBG w/o vest	8.4 G (±0.7)

4.2 During the remainder of the gradual onset exposure, the portion in which the subjects used the AGSM, most of the subjects continued up to 9 G during Conditions III - V. The mean values for Conditions I - V were 8.8 G (±0.4), 8.7 G (±0.4), 9.0 G (±0.1), 9.0 G (±0) and 9.0 G (±0.2), respectively. There was no significant difference in endpoint among the five conditions for this part of the GOR. (Table 9 in the Appendix shows the subjects' individual performance)

4.3 The results for the relaxed rapid onset runs were calculated as the sum of the time a subject completed at each G-level attempted. Thus, the maximum possible time for each condition was 90 seconds (six 15-second runs from +4 to +9 Gz). As an example, a reported time of 50 seconds would represent completion of the 4 G exposure (15 seconds), 5 G exposure (30 sec total), 6 G (45 sec total), and the first 5 seconds of the 7 G exposure (50 sec total). The mean times for the relaxed rapid onset runs with the five conditions are shown in Table 2 (individual times for the subjects are provided in the

Appendix – Table 10). The G-tolerance times for Conditions IV and V were significantly greater ($p<0.01$) than that of Condition I. The mean time for Condition V was also significantly greater ($p<0.05$) than that of Condition II. Four G-induced loss of consciousness (G-LOC) episodes occurred in three subjects (one aircrew) during this series of relaxed rapid onset runs. They occurred with no vest with PBG_{60} (one each at 7 G, 8 G, and 9 G) and no vest with PBG_{45} (at 8 G). These were the only GLOC incidents that occurred during the study. Thus, there were no GLOC episodes when subjects were free to utilize the AGSM.

Table 2. Mean Time Completed During Relaxed Rapid Onset Runs

Condition	Amount of PBG and Vest Status	Seconds Completed
I	No PBG	49 seconds (±17)
II	30 mm Hg PBG w/o vest	52 seconds (±18)
III	45 mm Hg PBG w/o vest	55 seconds (±17)
IV	60 mm Hg PBG with vest	59 seconds (±16)
V	60 mm Hg PBG w/o vest	62 seconds (±15).

4.4 During the subsequent series of rapid onset runs with use of the AGSM, most of the subjects were able to complete the series all the way through 9 G (which, of the possible 90 second total, was equal to the time period 75-90 seconds). Since this series began for each subject at the G-level he/she failed to complete during the relaxed ROR series, the time score for each subject included a credit for those G-levels below their starting point. The mean times for conditions I - V were 85 seconds (±7), 81 seconds (±13), 86 seconds (±11), 88 seconds (±5), and 87 seconds (±7), respectively. The times for Conditions III, IV, V were significantly greater ($p<0.05$) than that for Condition II only. Table 11 in the Appendix shows the total time for each subject.

4.5 Due to the volume of data, the subjects' ratings for discomfort and effort level, and their heart rates during G-exposure, are only reported for Conditions IV and V for the ROR exposures to 8 and 9G. The mean values for the 11 subjects are shown in Table 3 (individual subject ratings and heart rates are provided in the Appendix in Tables 12, 13, and 14). There was no significant difference between Conditions IV and V for any of the three measures.

4.6 The results for the SACM are expressed in terms of the subjects' G-dose and root-mean-square (RMS) for each of the five test conditions. G-dose represents the subjects' ability/willingness to track the target through each 10-second +9 Gz peak of the SACM. The value of the G-dose was determined by measuring the time and amount each subject exceeded 6 G during each 9 G peak (essentially taking the area of the G-exposure curve above 6 G). The 6 G level was selected since current instructions require wear of the vest during flights that will include exposure to 6 G or higher. Perfectly following a target through a 9 G peak would produce a G-dose of 33.5 G-seconds.

4.7 The RMS of the target tracking error is a measure of the subjects' performance through each peak of the SACM. For calculation of the RMS, each peak was considered to begin at 5 G at five seconds prior to the start of the subsequent 9 G

Table 3. Mean Discomfort / Effort Ratings and Heart Rates for ROR Exposures Using the AGSM

	Condition IV (60 mm Hg PBG with vest)	Condition V (60 mm Hg PBG w/o vest)
Discomfort Rating ROR with AGSM – 8G run	3.1 units (±2.0)	2.5 units (±2.5)
Discomfort Rating ROR with AGSM – 9G run	3.0 units (±1.38)	2.8 units (±2.2)
Effort Level Rating ROR with AGSM – 8G run	4.3 units (±2.4)	3.6 units (±2.7)
Effort Level Rating ROR with AGSM – 9G run	4.7 units (±2.4)	3.7 units (±2.6)
Peak Heart Rate ROR with AGSM – 8G run	148 bpm (±17)	148 bpm (±20
Peak Heart Rate ROR with AGSM – 9G run	153 bpm (±9)	151 bpm (±14)

peak, continue through the 9 G peak, and end at 5 G at five seconds after the 9 G peak. The tracking error was measured by calculating the difference between the target G-level and the G-level a subject selected by closed-loop control, with a smaller error (and RMS) indicating a better performance.

4.8 One subject (a male centrifuge panel subject) could not endure all four SACM peaks at 9 G during any of the five PBG/vest/no-vest conditions. Consequently, that subject's data was eliminated in the comparison of the conditions for the SACM G-profiles, resulting in an n=10 instead of the n=11 used for analysis of the GOR and ROR G-profiles.

4.9 The mean values for the SACM G-dose and RMS score for each condition are shown in Table 4. The values are based on an average of 40 peaks at 9 G (10 subjects with 4 peaks each). With regard to G-dose, there was no significant difference between Conditions IV and V. However, the G-dose for both of those conditions was significantly greater ($p<0.01 – 0.03$) than that for Conditions I, II, and III. Additionally, the value for Condition III was significantly greater ($p< 0.05$) than that for Condition II. The mean RMS score was lowest (best) during Conditions IV and V, with no statistical difference between the two. There was also no statistical difference between conditions I, II, and III. The Condition IV score was statistically better than Conditions I, II, and III ($p<0.001 – 0.05$), while Condition V was only statistically better than Condition II ($p<0.005$).

4.10 Table 5 shows the mean subject values for heart rate, discomfort rating, and effort rating for the SACM exposures (individual subject values are provided in the Appendix in Tables 12, 13, and 14). Again, due to the volume of data, results are only reported for Conditions IV and V.

Table 4. Mean G-dose and RMS Score for SACM Exposures

Test Condition	G-dose **Higher** value = greater G-exposure	RMS Score **Lower** score = better performance
Condition I	23.64 (±4.49)	1.12 (±0.27)
Condition II	22.88 (±4.59)	1.11 (±0.28)
Condition III	25.70 (±2.76)	0.96 (±0.22)
Condition IV	27.91 (±2.30)	0.80 (±0.16)
Condition V	27.16 (±3.15)	0.89 (±0.28)

Table 5. Mean Discomfort Rating, Effort Rating, and Heart Rate for the SACM

	Condition IV (60 mm Hg PBG with vest)	**Condition V (60 mm Hg PBG w/o vest)**
Discomfort Rating 1st 9G peak of SACM	3.2 units (±1.1)	2.8 units (±1.5)
Discomfort Rating 4th 9G peak of SACM	4.6 units (±1.8)	4.8 units (±3.0)
Effort Level Rating All 9G peaks of SACM	5.2 units (±2.4)	5.4 units (±2.7)
Peak Heart Rate 1st 9G peak of SACM	148 bpm (±15)	140 bpm (±16)
Peak Heart Rate 4th 9G peak of SACM	156 bpm (±18)	159 bpm (±14)

4.11 After each subject completed the entire battery of five test conditions, he/she was asked to rank the different equipment conditions from 1 (best) to 5 (worst). The ranking was to be based on the subject's perception of comfort (including breathing effort) for each equipment condition during the multiple series of G-exposure, and how well he/she felt the condition supported their G-tolerance and -endurance. Mean ratings for the different conditions are shown in Table 6 (individual preferences are provided in Table 15 of the Appendix). Scores for Conditions IV and V were significantly better ($p<0.001$) than those for Conditions I and II. Additionally, the rating for Condition V was significantly better ($p<0.01$) than that for Condition III. All eleven of the subjects rated Condition I (no PBG) as the worst. Additionally, nine of the eleven subjects rated Condition II (30 mm Hg PBG with no vest) as the second worst. The five aircrew rated Condition V (60 mm Hg PBG with no vest) the best, but only one of the six centrifuge panel subjects chose that condition as the best. The majority of the panel subjects preferred 60 mm Hg PBG with the vest.

Table 6. Mean Rating of Best Overall Condition (score of 1 = best rating)

Condition	Amount of PBG and Vest Status	Rating
I	No PBG	5.0 (±0) worst
II	30 mm Hg PBG w/o vest	3.9 (±0.2)
III	45 mm Hg PBG w/o vest	2.5 (±0.6)
IV	60 mm Hg PBG with vest	2.0 (±1.0)
V	60 mm Hg PBG w/o vest	1.6 (±0.8) best

4.12 Along with the rating of the conditions, the subjects completed a questionnaire after Conditions II-V, comparing the just finished condition to the one just previous. Results are provided only for the two 60 mm Hg conditions, since they produced the best G-tolerance and highest subject acceptance. Also, results are shown for several additional questions the subjects answered after completion of the study. Results are reported separately for the five aircrew subjects and the six panel member subjects.

QUESTION: Compared to Condition IV (60 mm Hg of pressure breathing <u>with</u> a vest), how would you rate your ability to <u>inhale</u> during G when using 60 mm of pressure breathing <u>without</u> a vest?

1	2	3	4	5
Much Worse (or harder)		Same		Much Better (or easier)

Aircrew Responses	Panel Member Responses
	One marked "1"
	Two marked "2"
One marked "3"	Two marked "3"
Two marked "4"	
Two marked "5"	One marked "5"

QUESTION: Compared to Condition IV (60 mm Hg of pressure breathing <u>with</u> a vest), how would you rate your ability to <u>exhale</u> during G when using 60 mm Hg of pressure breathing <u>without</u> a vest?

1	2	3	4	5
Much Worse (or harder)		Same		Much Better (or easier)

Aircrew Responses	Panel Member Responses
	One marked "1"
	One marked "2"
Five marked "3"	Four marked "3"

QUESTION: Compared to Condition IV (60 mm Hg of pressure breathing with a vest), how would you rate your ability to perform the anti-G straining maneuver when using 60 mm Hg of pressure breathing without a vest?

1	2	3	4	5
Much Worse (or harder)		Same		Much Better (or easier)

Aircrew Responses	Panel Member Responses
	Four marked "2"
Two marked "3"	One marked "3"
Two marked "4"	
One marked "5"	One marked "5"

QUESTION: Compared to Condition IV (60 mm Hg of pressure breathing with a vest), how would you rate your overall fatigue level at the end of the centrifuge session when using 60 mm Hg of pressure breathing without a vest?

1	2	3	4	5
Much Worse		Same		Much Better

Aircrew Responses	Panel Member Responses
	One marked "1"
	Three marked "2"
Two marked "3"	One marked "3"
Two marked "4"	One marked "4"
One marked "5"	

QUESTION: With respect to your aircraft, do you want to keep PBG?

Yes _____ No _____ Can't tell at this time _____

Aircrew Responses	Panel Member Responses
"Yes, definitely"	Not applicable
"Yes"	
"Yes, absolutely"	
"Yes"	
"Yes, PBG is a great addition"	

QUESTION: If yes, what level of PBG (with or without a vest) would you want?

30 mm Hg___ 45 mm Hg___ 60 mm Hg___ Other ___

Aircrew Responses	Panel Member Responses
All five marked "60 mm Hg"	Not applicable

QUESTION: If you want to keep PBG, would you want the highest breathing pressure to start at a lower G-level (that is, change the current COMBAT EDGE delivery schedule for PBG)?

Yes _____ No _____ Can't tell at this time _____

Aircrew Responses	Panel Member Responses
All five marked "No"	Not applicable

QUESTION: If you want to keep PBG, do you feel the vest is necessary in order to maintain your G-tolerance?

Yes _____ No _____ Can't tell at this time _____

Aircrew Responses	Panel Member Responses
All five marked "No"	Not applicable

5.0 DISCUSSION:

ACC Concern: Is positive pressure breathing for G-protection necessary?

Answer: Yes - the results of this study indicate a combination of PBG and the AGSM produces greater G-tolerance and better user acceptance than use of the AGSM by itself.

5.1 When PBG was not used, relaxed gradual-onset G-tolerance was significantly lower than that produced by use of PBG at 45 or 60 mm Hg (6.7G vs 8.0 – 8.4G). Also, use of 60 mm Hg of PBG produced greater G-tolerance than no PBG during both relaxed rapid-onset and SACM G-exposures. These results agree with those of previous studies that showed positive effects of PBG for both G-tolerance (Shaffstall and Burton 1979; Bagshaw 1986; Pecaric and Buick 1992; and Burns et. al. 2001) and G-endurance (Burns and Balldin 1988; and Albery 1997).

5.2 The G-tolerances recorded in this study may have been affected by the order of the five experimental conditions. That is, since the no PBG condition occurred first for each subject, their individual G-tolerance may have increased over the course of the study and produced higher values for subsequent test conditions. However, the subjects' comments and discomfort ratings also indicated that having PBG was preferable to not having it. All eleven subjects rated Condition I (no PBG) as the least desirable. Their ratings were based on breathing difficulties during the G-exposures, particularly at higher G-levels. The G-suit inflation, the increased weight of the chest wall with increasing G, and the breathing resistance of the oxygen mask, hose, and regulator, made it difficult for them to obtain a sufficient volume of air. That difficulty was greatly reduced with the use of PBG at 45 or 60 mm Hg. All of the aircrew subjects expressed a desire to maintain use of PBG in their aircraft.

5.3 It should be noted that PBG has been shown to be most effective when used in combination with a full-coverage G-suit (Albery 1997; Tong et. al. 1998; and Burns et. al. 2001). That combination has been selected by the Royal Air Force for use in their Typhoon aircraft, by the Swedish Air Force for use in their Gripen, and by the Finnish Air Force for use in their F-18 aircraft.

ACC Concern: "Evaluate different levels of PPB without the chest counter pressure garment. Determine the optimal level of PPB and G protection without the upper counter pressure vest."

Answer: The best G-protection was provided by use of 60 mm Hg peak PBG, with or without the vest.

5.4 The subjects' mean comfort ratings were also best for the two 60 mm Hg conditions. Thus, the current CE PBG schedule proved to be highly effective. However, due to constraints on subject availability that schedule was the only one used in this study and, consequently, it is not possible to say definitively that it is the most acceptable schedule.

5.5 In order to tolerate the head-to-foot inertial loading that occurs during +Gz exposure, aircrew must be able to maintain adequate arterial blood pressure at head level. This is done through use of the G-suit, the AGSM, and PBG. Because PBG can elevate blood pressure without the fatiguing muscular effort required as part of the AGSM, use of high levels of PBG should theoretically provide better and more comfortable G-protection than lower amounts of PBG.

5.6 Pecaric and Buick (1992) investigated the effect of 0, 18, 38, 60, and 73 mm Hg of assisted PBG on relaxed GOR G-tolerance in an effort to describe the amount of PBG required by relaxed subjects to reach high sustained +Gz levels. They found that each step increase in PBG improved G-tolerance, except when 73 mm Hg was compared to 60 mm Hg. There was no statistical difference between those two conditions. However, the authors stated that 73 mm Hg may not have been an adequate increase in PBG over 60 mm, and proposed that a PBG schedule that begins at +3.3 Gz and increases mask cavity pressure at 42 mm Hg/+Gz to at least 73 mm Hg would provide the best G-protection to the broad pilot population.

5.7 Burns and Balldin (1988) compared 50 and 70 mm Hg of assisted PBG to a standard G-suit and AGSM combination (no PBG) during a 5-9 +Gz SACM profile to exhaustion. Their results showed a significant increase in mean SACM tolerance time for PBG_{50} (115%) and PBG_{70} (88%) compared to the no PBG condition. Theoretically, PBG_{70} should have provided the greatest amount of protection. However, the subjects experienced discomfort from nasopharynx distension caused by the high amount of pressure breathing and a necessarily tighter fitting oxygen mask, and the discomfort affected their tolerance times. Also, too high a PBG level will decrease cardiac output, which will tend to lower the G-tolerance. The subjects in the Pecaric and Buick (1992) study also perceived an increase in nasopharyngeal distension from the 60 to 73 mm Hg

PBG levels, but the distension was not considered a cause of premature termination of the G-exposures.

5.8 For the Gripen aircraft, the Swedish Air Force uses a 4G starting point for PBG with a 10 mm Hg/G increase to a maximum of 50 mm Hg at +9 Gz. The Royal Air Force and Finnish Air Force also use a 4G starting point, and the same 12 mm Hg/G increase as CE.

5.9 All of the aircrew in this study indicated they did not see a need to change the current CE delivery schedule for PBG. That is, they preferred to keep the 4G starting point, 12 mm Hg/G rate of increase, and peak pressure of 60 mm Hg. One advantage of that starting point and rate is that communication is not hampered as much as it would be by a more ambitious PBG schedule.

ACC Concern: "Report the marginal G benefit with and without the upper counter pressure vest."

Answer: The results of this study indicate the counter-pressure vest can be eliminated without comprising an individual's ability to reach high G-levels during short periods of G-exposure.

5.10 Comparing G-tolerance during the GOR and ROR G-exposures, and during the short duration SACM, no statistical difference was found between wear or non-wear of the counter-pressure vest when using 60 mm Hg of PBG at +9 Gz. Additionally, performance of the tracking task with 60 mm Hg PBG during the SACM was not affected by removal of the vest.

5.11 With one exception (subject #1), there was no indication that elimination of counter-pressure during PBG increased subject discomfort levels. The subjects' ratings for discomfort and effort following the ROR with AGSM exposures showed no significant differences between the two 60 mm Hg conditions. The same was true for the effort ratings following the SACM. Indeed, the no vest 60 mm Hg PBG condition had the best mean subjective rating for overall comfort. Four of the aircrew indicated they found it easier to perform the AGSM without the vest, because they felt they could inhale easier at high-G. Also, several stated that the slight effort needed to exhale during PBG, with or without the vest, helped to reinforce the AGSM. The post-exposure questionnaires revealed a clear preference by the aircrew for use of 60 mm Hg PBG without the vest, while the majority of the panel subjects found use of the vest at 60 mm Hg to be slightly more preferable. The difference may be a matter of context. The aircrew can relate the benefit or non-benefit of the vest to their total workload in the cockpit, while the panel subjects' rating is based only on centrifuge experience.

5.12 Subject #1 rated the no vest 60 mm Hg condition below the 60 mm Hg with vest and 45 mm Hg without vest conditions due to a difficulty with exhalation during the SACM. He stated the exhalation problem did not exist during the straining rapid-onset runs. He did not have a similar problem during the 45 mm Hg no vest condition, and actually rated that condition equal in comfort to the 60 mm Hg with vest condition. At times during the relaxed GOR exposures of the no vest 60 mm Hg condition, subject #1 also mentioned difficulties with inhalation. The regulator was inspected and no problems were noted. He continued with the same regulator for the remainder of the exposures and reported no further problems of that nature. Due to a limited window of availability, subject #1 completed all of the test conditions before most of the subjects began the study. Consequently, he finished the study before the mask-leak-test period was extended to approximately 30 seconds to allow the subjects more time to experience the effort of exhaling against positive pressure without benefit of a vest. Many of the subjects reported that the effort to exhale at 8 and 9G was similar to or slightly less than the effort required during the mask-leak-test.

5.13 Due to the design of this study, it is not possible to say if use of PBG without chest counter-pressure will result in unacceptable breathing fatigue over the course of several sorties, or in a single sortie with G-exposures more demanding than those represented by the SACM. The CE vest was included in the original ensemble design to both reduce breathing fatigue and reduce the possibility of chest over-distension due to PBG. Centrifuge studies have shown the benefits of assisted PBG in reducing fatigue over multiple G-exposures (Tong et. al. 1998; and Balldin et. al. 2003). A controlled operational test would help determine if PBG without chest counter-pressure also helps reduce fatigue when used for multiple sorties, or if unforeseen effects arise in the operational environment. Cresswell et. al. (1988) described the results of a flight trial using PBG up to 45 mm Hg with and without chest counter-pressure. While PBG without counter-pressure proved subjectively acceptable, PBG with counter-pressure was shown to be significantly more effective.

5.14 The Swedish Defence Research Agency recently completed a centrifuge study using PBG up to 50 mm Hg with and without chest counter-pressure. The study was a continuation of the work reported earlier by Gronkvist et. al. (2003). While results of the study are still being analyzed, the following was obtained by personal communication with the investigators. Twenty subjects, the majority of whom were pilots of Gripen aircraft, completed exposures to +9 Gz. Ten of the subjects also completed an SACM to exhaustion. The subjects wore a counter-pressure vest (similar to the CE vest) for all exposures. For the exposures without counter-pressure, the vest was not inflated. There were no medical complications, unexpected side effects, or G-LOCs during any of the exposures. Non-inflation of the vest did not appear to induce any deleterious effects on relaxed G-level tolerance nor on G-endurance.

Aeromedical Aspects of Elimination of Chest Counter-Pressure:

5.15 The subjects in this study reported no adverse affects due to chest or lung over-distension during unassisted PBG. As mentioned in the initial background section, a survey of human pulmonary tolerance to dynamic over-pressure by Krebs and Pilmanis (1996) concluded that an unsupported chest wall should safely support 80 mm Hg static and dynamic over-pressure of the lungs. That same limit of 80 mm Hg is stated in the textbook *Aviation Medicine* by Ernsting and King (1988). When wearing chest and abdomen support devices and with active breathing muscles, the safe pressure may reach as high as 190 mm Hg (Krebs and Pilmanis, 1996). Pilots actively executing an AGSM during high-G exposure have an active muscle support of the chest wall and the inflated abdominal bladder of the G-suit supporting the diaphragm. This should protect them from over-expansion of the lungs even without a counter-pressure vest. On the other hand, if a G-LOC occurs during unassisted PBG at high-G, the respiratory muscle support of the chest wall disappears, which may increase the risk of over-expansion of the lungs with a slight possibility of lung rupture with pneumothorax and even cerebral arterial air embolism as a result. This risk is minimized however, during high-G by the inflated abdominal bladder preventing downward expansion of the lungs and by the weight of the thorax wall and flight equipment worn over the thorax.

5.16 Green (1995), in a study of changes in lung volume subdivisions under high Gz acceleration and PBG, reported it appeared that acceleration and G-suit inflation (in this case a full-coverage suit with a circumferential abdominal bladder) were greater determinants of lung volume than PBG. Study results showed a progressive reduction in vital capacity with increasing +Gz acceleration despite the presence of PBG, such that at +9 Gz, with a breathing pressure of 65 mm Hg, vital capacity was less than 50% of the +1 Gz value. He stated it may be postulated that sufficient counter-pressure is provided by the G-suit abdominal bladder and the increased weight of the chest wall during acceleration, and as a result the addition of a chest counter-pressure garment is unnecessary. However, he cautioned that if the reduction in lung volume caused by G-suit inflation and Gz acceleration is balanced by an increase in lung volume caused by using PBG without chest counter-pressure, it is important to determine in which regions of the lung the changes are occurring. It may be that expansion of the lung volume only occurs apically (from PBG), while the basal airways remain closed (from acceleration and abdominal bladder action). Safety implications are unknown for such an expansion.

5.17 The risk of a spontaneous pneumothorax without over-expansion of the lungs has been described in the general population as relatively common in tall, thin, young, healthy males with an incidence rate ranging from 2–46 per 100,000. The risk seems to be somewhat higher in the military population (Voge 1986). The risk is not necessarily associated with physical exercise and may occur during resting conditions, even during sleep. Spontaneous pneumothorax affects males 5-10 times more than females. It is usually ascribed to a rupture of an apical subpleural bleb or bulla in the lungs. Over-expansion of the lungs during unassisted pressure breathing in a G-LOC'd pilot might increase this risk in individuals with such a pre-existing medical condition.

5.18 Four G-LOC incidents occurred in this study – all during PBG without counter-pressure (Conditions III (one incident) and V (three incidents)). The G-LOCs were during the relaxed ROR exposures and may have been due to the subjects' comfort with remaining relaxed as the G–levels increased. That is, they may have waited too long to release the hand brake after reaching the light loss criteria. There were no G-LOCs during the exposures incorporating the AGSM. One of the Condition V incidents occurred at 9G, which means the subject was breathing 60 mm Hg PBG at the time. All of the subjects recovered as soon as the G-level decreased and reported no discomfort of any kind. They were able to complete the remainder of the G-exposures for that day with no additional rest required.

5.19 Table 7, below, shows previous centrifuge and non-centrifuge studies that used positive pressure breathing (PPB) without chest counter-pressure and did not report any subjects suffering adverse effects.

Table 7. Studies Using Unassisted PPB With No Evidence of Lung Over-Distension

Study Author	Number of Subjects	Peak Level of PPB (mm Hg)	+Gz Level for Onset of Peak PPB
Shaffstall & Burton	8	30 mm	1 G
Shubrooks	10	40 mm	1 G
Cresswell et. al. [1]	7	45 mm	8 G
Balldin and Wranne [2]	5	50 mm	1 G
Gronkvist et. al.[2, 3]	20	50 mm	9 G
Green [2]	7	52 mm	7 G
Meehan	5	60 mm	1 G

Note 1: Study consisted of a flight trial
Note 2: Subjects wore chest counter-pressure but it was not inflated
Note 3: Numbers obtained by personal communication; data being analyzed for publication

5.20 Along with the possibility of chest over-distension due to normal PBG delivery, pressure within the lungs may exceed the recommended 80 mm Hg limit if a rapid loss of cabin pressure occurs during use of PBG. Altitude chamber tests during the development of CE showed that mask cavity pressures could exceed 100 mm Hg during a one-second five pounds-per-square-inch decompression with assisted PBG above 5Gs. The CE Aeromedical Systems Safety Working Group (ASSWG) of that time accepted the system performance due to the low probability of occurrence of decompressions of that nature, the presence of a chest counter-pressure vest, and the safety margin inherent in the CE pressure spike limitation of 80 mm Hg with $\leq$250milliseconds between 80–100 mm Hg. It is not known to what degree removal of the vest would increase risk during such a decompression. Additionally, some functional failures of the CE breathing regulator could allow mask pressure to exceed 80 mm Hg or PPB to occur when not required. The regulator Failure Mode and Effects Analysis (FMEA) assigns a severity code and probability of failure to these scenarios of minor/improbable and minor/remote, respectively. However, since the FMEA was conducted with wear of a counter-pressure vest in mind, it would be prudent to re-evaluate the results based on elimination of the vest.

5.21 The ASSWG requested an epidemiological study of pilots using PBG during initial operational use in order to determine the safety of the system. As part of that process, Travis and Morgan (1994) conducted a survey of pilots during the operational test and evaluation of CE to determine the impact of PBG on mission accomplishment and on the incidence of acute adverse health effects. With the exception of dry cough, no significant increases in adverse events were found. A similar type effort completed in conjunction with an operational test of unassisted PBG would help ensure that unassisted PBG is both safe and operationally effective.

Other Considerations

a. Use of the CSU-17/P Counter-Pressure Vest for Altitude Protection:

5.22 Pressure breathing for altitude (PBA), combined with high concentrations of oxygen, is used to prevent hypoxia when aircrew are exposed to cabin altitudes above 40,000 feet. PBA differs from PBG in two respects: 1) it is an emergency procedure (intended to allow aircrew to descend to a safe altitude following a loss of pressurization); and 2) it can, and normally does, occur at 1G. The amount of PBA delivered depends on the altitude of exposure and the PBA schedule of the breathing regulator. As the altitude increases, the PBA must increase to maintain an acceptable level of total pressure within the lungs. The CRU-93/A and CRU-98/A regulators deliver a maximum of 30 mm Hg of PBA, the minimal amount of PBA adequate for exposure to 50,000 feet. The F/A-22 Breathing Regulator Anti-G (BRAG) Valve has an enhanced PBA schedule to provide both greater overall hypoxia protection and protection up to 60,000 feet. At 50,000 feet, the BRAG Valve delivers approximately 60 mm Hg. The breathing pressure builds to 70 mm Hg at 53,000 feet, and is maintained at that pressure up to the operational ceiling of 60,000 feet.

5.23 While PBA is necessary for hypoxia protection at extreme altitudes, the high breathing pressures can cause problems of their own. The chest becomes distended due to the pressure, and the work of breathing increases, particularly during exhalation. The increased breathing effort can lead to hyperventilation. Pressure breathing at 30 mm Hg causes, on average, an increase in the respiratory minute volume averaging about 50% greater than the resting value (Ernsting and King 1988). The concern with hyperventilation is the decrease it can cause in blood levels of carbon dioxide, leading to a decrease in blood flow to the brain and an increased level of hypoxia. Individuals trained in pressure breathing are certainly better at controlling their chest expansion and breathing rate and volume. However, even well-trained individuals can find it difficult to control their breathing as pressures increase above 30 mm Hg at 1G (this is not the case during high G-levels). That breathing difficulty is reduced by use of counter-pressure, such as the CE vest.

5.24 The CRU-94/P ITB ensures that when PBA is delivered to the oxygen mask an equal amount of pressure is delivered to the counter-pressure vest. Additionally, in the F/A-22, the BRAG Valve delivers pressure to the G-suit during PBA. The combination of vest and G-suit inflation is designed to reduce the work of breathing, limit distension of the chest, and help prevent pooling of blood in the lower body. Certainly, without chest counter-pressure, breathing pressures at 1G that approach 50 mm Hg become extremely difficult to tolerate, even for individuals well-trained in pressure breathing. Aviation medicine textbooks advise use of counter-pressure for PBA above 30 mm Hg. For these reasons, the CSU-17/P counter-pressure vest should be worn during F/A-22 flights at 45,000 feet or higher.

b. Use of the CRU-94/P ITB Without the Vest:

5.25 As mentioned above in the methods section, the portion of the CRU-94/P ITB that connects to the counter-pressure vest contains a relief valve. When the vest is not attached that relief valve is exposed to the immediate environment, and will open when the pressure of breathing gas inside the CRU-94/P exceeds approximately 38 mm Hg. Thus, during PBG without the vest, the relief valve will begin to vent breathing gas at just above 7G unless the vest attachment port is plugged or the valve is modified to relieve at a higher pressure. For simplicity sake, in this study the port was plugged for PBG conditions without the vest. For flight purposes, it would be preferable to maintain the relief capability of the CRU-94/P by adjusting the cracking point of the valve. The exact opening point should be determined in conjunction with a review of the breathing regulator Failure Mode and Effects Analysis. The opening point would require readjustment to over 60 mm Hg due to the CE PBG delivery schedule.

6.0 CONCLUSIONS:

6.1 Use of a combination of PBG and the AGSM enhances G-tolerance and user comfort more than use of the AGSM alone.

6.2 The starting point, rate of increase, and peak pressure of the current CE PBG delivery schedule improves subject G-tolerance without adversely impacting subject comfort.

6.3 Elimination of the counter-pressure vest during use of CE supplied PBG does not hinder an individual's ability to reach +9 Gz or complete a short duration SACM.

6.4 It is not known if use of PBG without chest counter-pressure will increase fatigue during multiple sorties, or produce other unanticipated performance or aeromedical effects in an operational environment.

7.0 RECOMMENDATIONS:

Based on the above discussion and conclusions, AFRL/HEP has the following recommendations.

7.1 ACC should continue to use PBG according to the current delivery schedule of the COMBAT EDGE system.

7.2 ACC should conduct an operational trial to verify the safety and effectiveness of use of COMBAT EDGE without the counter-pressure vest in a flight environment.

7.3 Aircrew should wear the CSU-17/P vest (or similar counter-pressure) during any flight that reaches an altitude where greater than 30 mm Hg of PBA will occur following a loss of cabin pressurization (e.g. F/A-22 at 45,000 feet or higher).

7.4 If use of PBG without counter-pressure is shown to be operationally acceptable, ACC should investigate modification of the relief valve of the CRU-94/P integrated terminal block to permit use of the CRU-94/P with PBG up to 60 mm Hg when the vest is not attached (i.e. modify the relief valve to open above 60 mm Hg).

7.5 If use of PBG without counter-pressure is shown to be operationally acceptable, ACC should support a manufacturer's review of the CE breathing regulator Failure Mode and Effects Analysis to determine if any safety related changes of the regulator are warranted.

8.0 REFERENCES:

Albery WB. Evaluation of Six G Protection Ensembles During 5 to 9 G Simulated Aerial Combat Maneuvers. SAFE J. Vol. 27, No. 2, 92-99, 1997.

Bagshaw M. A trial of positive pressure breathing during acceleration in air combat manoeuvres at an RAF tactical weapons unit. (Abstract) Aviat. Space Environ. Med. May 1986 pg 496.

Balldin UI, Wranne B. Hemodynamic effects of extreme positive pressure breathing using a two-pressure flying suit. Aviat Space Environ Med. 1980; 51:851-5.

Balldin UI, O'Connor RR, Werchan PM, Isdahl WM, Demitry PF, Stork RL, Morgan TR. Heat stress effects for USAF anti-G suits with and without a counter-pressure vest. Aviat. Space Environ. Med. 2002; 73:456-9.

Balldin UI, Werchan PM, French J, Self B. Endurance and performance during multiple intense high +Gz exposures with effective anti-G protection. Aviat. Space Environ. Med. 2003; 74:303-8.

Burns J, Balldin UI. Assisted positive pressure breathing for augmentation of acceleration tolerance time. Aviat. Space Environ. Med.1988; 59:225-33.

Burns JW, Ivan DJ, Stern CH, Patterson JC, Johnson PC, Drew WE, Yates JT. Protection to +12 Gz. Aviat. Space Environ Med 2001; 72; 413-21.

Cresswell GJ, McPhate D, Harding RM, Farmer EW. Positive pressure breathing with and without chest counterpressure – an assessment in air combat manoeuvring flight. (Abstract) Aviat. Space Environ. Med. May 1988 pg 480

Ernsting J. and King P. (1988) *Aviation Medicine*: Chapter 6, pg 66-67, Butterworths & Co Ltd

Fernandes L, Linder J, Krock LP, Balldin UI, Harms-Ringdahl K. Muscle activity in pilots with and without pressure breathing during acceleration. Aviat Space Environ Med. 2003; 74:626-32.

Green ND. Lung volume changes under positive pressure breathing for G protection. Royal Air Force School of Aviation Medicine Report No 01/95, July 1995.

Gronkvist M, Bergsten E, Kolegard R, Gustavsson P, Eiken O. Is the counter-pressure jerkin needed during positive pressure breathing at high +Gz-loads? (Abstract). Aviat Space Environ Med. 2003; 74: 469-70.

Krebs MB, Pilmanis AA. Human pulmonary tolerance to dynamic over-pressure. United States Air Force Armstrong Laboratory report AL/CF-TR-1996-0058. Brooks Air Force Base, Texas. 66 pages.

Meehan JP. Investigation to determine the effects of long-term bed rest on G-tolerance and on psychomotor performance. Final Report for NASA Manned Spacecraft Center. Contract No. NAS 9-3500. 1966. University of Southern California, Los Angeles.

Morgan, Brown, Murray Burns. Positive pressure breathing for G: Evolution and promise. Physiologist. 1992; 35(1):S151-4.

Pecaric M, Buick F. Determination of a pressure breathing schedule for improving +Gz tolerance. Aviat. Space Environ. Med. 1992; 63: 572-8.

Shaffstall RM, Burton RR. Evaluation of assisted positive pressure breathing on +Gz tolerance. Aviat. Space Environ. Med. 50(8): 820-824, 1979.

Shubrooks SJ. Positive-pressure breathing as a protective technique during +Gz acceleration. J. Appl. Physiol. 35(2): 294-298.

Tong A, Balldin UI, RC Hill, Dooley JW. Improved anti-G protection boosts sortie generation ability. Aviat. Space Environ. Med.1998; 69:117-20

Travis TW, Morgan TR. U.S. Air Force positive-pressure breathing anti-G system (PBG): subjective health effects and acceptance by pilots. Aviat. Space Environ. Med. 1994; 65(5, Suppl.):A75-9.

Voge VM, Anthracite R. Spontaneous pneumothorax in the USAF aircrew population: a retrospective study. Aviat. Space Environ. Med. 1986; 57: 939-49.

9.0 APPENDIX - Figures and Tables:

Figure 1. CSU-17/P Counter-pressure Vest

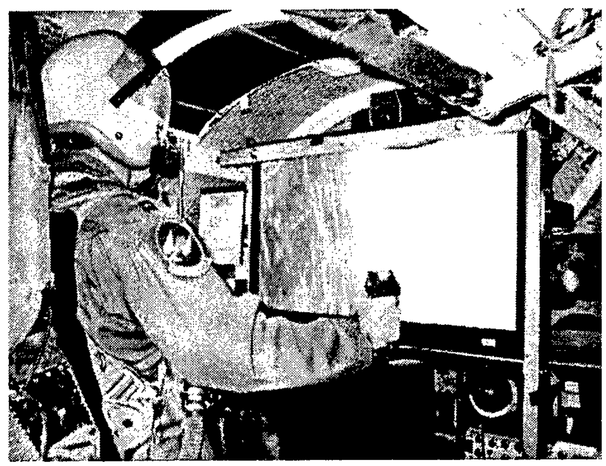

Figure 2. Display of closed-loop target tracking task in the centrifuge gondola.

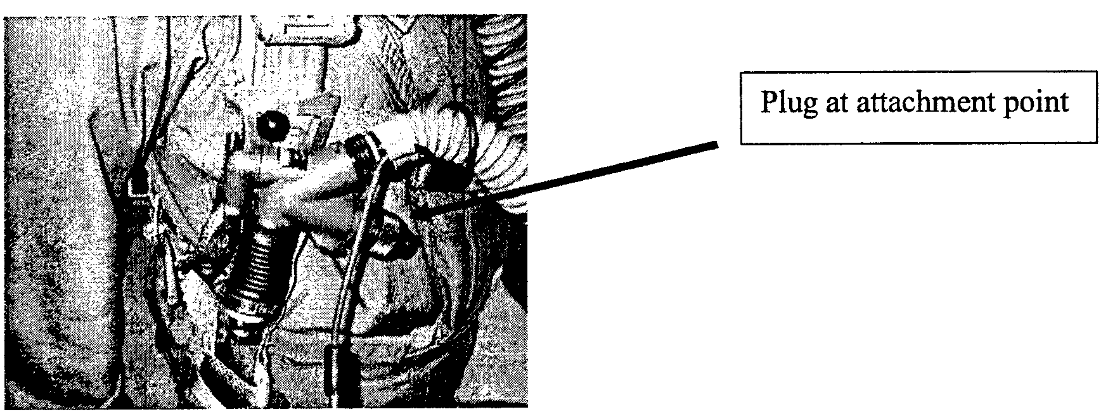

Figure 3. Plug used to seal the part of the CRU-94/P Integrated Terminal Block where the counter-pressure vest is attached.

Table 8. Relaxed Portion of the GOR (G-Level obtained)

Subject	CONDITION				
	No PBG no vest	PBG 30 No vest	PBG 45 no vest	PBG 60 with vest	PBG 60 no vest
1	6.5	5.5	9	7	8.1
2	7.6	#	7	#	9
3 (f)	5.8	7	8.2	9	9
4	6.9	9	9	9	9
5	8.1	8	8.3	8.4	8.6
6 *	5	5.8	6.5	6.8	7.2
7 *	8	9	9	9	9
8	6.9	7.8	8.1	9	8.1
9 *	7.9	8.9	9	9	9
10*	5.5	5.7	6.8	7.5	8.4
11* (f)	5.6	4.2	6.9	7.5	7.2
Average	6.7	7.1	8.0	8.2	8.4
SD	1.1	1.7	1.0	0.9	0.7

(f) = female, * = aircrew, # = missing data

Table 9. G-level Obtained During the Portion of the GOR that Included Use of the AGSM

Subject	CONDITION				
	No PBG no vest	PBG 30 no vest	PBG 45 no vest	PBG 60 with vest	PBG 60 no vest
1	9	8.9	9	9	8.5
2	8.8	8.7	8.9	9	9
3 (f)	9	7.9	9	9	9
4	9	9	9	9	9
5	9	9	9	9	9
6 *	7.8	9	9	9	9
7 *	9	9	9	9	9
8	8.2	8	8.9	9	9
9 *	9	9	9	9	9
10*	9	9	9	9	9
11* (f)	9	8.7	8.8	9	9
Average	8.8	8.7	9.0	9.0	9.0
SD	0.4	0.4	0.1	0.0	0.2

(f) = female, * = aircrew

Table 10. Relaxed Rapid Onset Runs (seconds completed)

	CONDITION				
Subject	**No PBG no vest**	**PBG 30 No vest**	**PBG 45 no vest**	**PBG 60 with vest**	**PBG 60 no vest**
1	38	40	52	54	54
2	55	45	45	60	60
3 (f)	45	54	37	53	45
4	69	79	79	90	90
5	60	40	69 **	52	65 **
6 *	59	58	69	54	69
7 *	39	51	50	51	42
8	82	90	75	90	83 **
9 *	39	41	54	54	69
10*	25	52	52	38	50
11* (f)	30	26	23	52	53 **
Average	49	52	55	59	62
SD	17	18	17	16	15

(f) = female, * = aircrew, ** G-LOC

Table 11. Rapid Onset Runs that Included Use of the AGSM (total seconds completed)

	CONDITION				
Subject	**No PBG no vest**	**PBG 30 no vest**	**PBG 45 no vest**	**PBG 60 with vest**	**PBG 60 no vest**
1	79	79	90	90	90
2	75	60	75	75	75
3 (f)	82	90	90	90	90
4	90	90	90	90	90
5	90	81	90	84	90
6 *	90	90	90	90	90
7 *	90	90	90	90	85
8	90	90	90	90	90
9 *	90	90	90	90	90
10*	90	72	90	90	90
11* (f)	70	54	56	87	72
Average	85	81	86	88	87
SD	7	13	11	5	7

(f) = female, * = aircrew

Table 12. Discomfort Rating - Scale is 0 (nothing at all) to 11 (maximal)

Subject	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest
	ROR with AGSM 8 G		ROR with AGSM 9 G		SACM (fourth peak)	
1	6	5	6	7	7	9
2	7	8	#	#	#	#
3 (f)	2	2	3	2	3	3
4	#	#	2	2	2	3
5	1	3	3	5	6	6
6 *	2	1	2	3	4	3
7 *	3	2	4	3	6	6
8	#	#	2	3	3	10
9 *	2	0	4	0	7	1
10 *	3	0.5	2	0	3	2
11 * (f)	2	1	2	#	5	5
Average	3.1	2.5	3.0	2.8	4.6	4.8
SD	2.0	2.5	1.3	2.2	1.8	3.0

(f) = female, * = aircrew, # = missing data

Table 13. Effort Rating - Scale is 0 (nothing at all) to 11 (maximal)

Subject	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest
	ROR with AGSM 8 G		ROR with AGSM 9 G		SACM	
1	9	7	9	9	9	10
2	8	9	#	#	#	#
3 (f)	3	2	3	3	3	2
4	#	#	2	2	2	3
5	3	4	8	7	7	6
6 *	3	2	4	3	5	5
7 *	3	2	4	3	5	5
8	#	#	3	3	3	10
9 *	3	1	7	1	7	3
10 *	4	2	4	2	8	5
11 * (f)	3	3	3	#	3	5
Average	4.3	3.6	4.7	3.7	5.2	5.4
SD	2.4	2.7	2.4	2.6	2.4	2.7

(f) = female, * = aircrew, # = missing data

Table 14. Heart Rate (beats per minute)

Subject	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest	PBG_{60} Vest	PBG_{60} No Vest
	ROR with AGSM 8 G		ROR with AGSM 9 G		SACM (fourth peak)	
1	145	149	150	162	135	149
2	115	115	#	#	#	#
3 (f)	138	127	150	140	150	150
4	#	#	150	145	155	155
5	170	160	165	168	180	175
6 *	155	150	155	152	170	165
7 *	160	168	150	135	162	157
8	#	#	140	147	145	150
9 *	150	137	155	137	125	140
10 *	155	170	170	172	180	187
11 * (f)	140	156	148	#	155	162
Average	148	148	153	151	156	159
SD	17	20	9	14	18	14

(f) = female, * = aircrew, # = missing data

Table 15. Rating of Best Condition (1 = best)

Subject	CONDITION No PBG no vest	PBG 30 no vest	PBG 45 no vest	PBG 60 with vest	PBG 60 no vest
1	5	3.5	1.5	1.5	3.5
2	5	4	3	1	2
3 (f)	5	4	3	1	2
4	5	4	3	1	2
5	5	3.5	2	3.5	1
6 *	5	4	3	2	1
7 *	5	4	2	3	1
8	5	4	3	1	2
9 *	5	4	2	3	1
10*	5	4	2	3	1
11* (f)	5	4	3	2	1
Average	5.0	3.9	2.5	2.0	1.6
SD	0	0.2	0.6	1.0	0.8

(f) = female, * = aircrew

ABBREVIATIONS AND ACRONYMS

+Gz	Head–to–Foot Inertial Loading
ACC	Air Combat Command
AFRL	Air Force Research Laboratory
AGSM	Anti-G Straining Maneuver
ANOVA	Analysis of Variance
ASSWG	Aeromedical Systems Safety Working Group
BRAG	Breathing Regulator Anti-G
CE	COMBAT EDGE
CLL	Central Light Loss
COMBAT EDGE	Combined Advanced Technology Enhanced Design G Ensemble
FMEA	Failure Mode and Effects Analysis
G-LOC	G-induced Loss of Consciousness
GOR	Gradual Onset Run
HEP	(AFRL) Biosciences and Protection Division
ITP	Integrated Terminal Block
mm Hg	Millimeters of Mercury
PLL	Peripheral Light Loss
PBA	Pressure Breathing for Altitude
PBG	Pressure Breathing for G
PPB	Positive Pressure Breathing
RMS	Root-Mean-Square
ROR	Rapid Onset Run
SACM	Simulated Air Combat Maneuver