FOREWORD

The work reported herein was performed under Project 7164, "High-Altitude Physiology," Task No. 716404, "Physiological Criteria for Extended Environments," for the Physiology Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories. The research was conducted from June 1958 until January 1959. This report complements WADC Technical Note 59-148, "Development of an Emergency Pressure Suit (Coveralls, High-Altitude, Type CSU-4/P)." Some of the human volunteers were USAF officers and airmen; others were students from the University of Dayton, Dayton, Ohio.

The author is especially indebted to Mrs. S. L. Peterson, Librarian, Aerospace Medical Library, Brooks AFB, Texas, for her two years of endeavor to secure rare manuscripts cited in this work, and to Marjorie Lisaura and Lenora Miller, Barksdale AFB, Louisiana, for their voluntary assistance in preparing this manuscript.

ABSTRACT

The CSU-4/P high-altitude bladder pressure suit was designed mainly for quick donning. Each of 15 subjects who wore the suit ensemble was rapidly decompressed from 282 mm Hg chamber pressure (7.6 km) to 42 mm Hg chamber pressure (19.8 km) in an average of 1.5 seconds and then further to 33.6 mm Hg (21.4 km). All subjects were able to remain at 33.6 mm Hg for 5 minutes without any difficulty. Each of 14 of the subjects was again successfully exposed to the same profile except that one hand was bare and the other hand was protected by an unpressurized leather flying glove. Eight subjects were easily able to remain at 8 to 3 mm Hg chamber pressure (30.6 to 36.7 km) continuously for 120 minutes. One subject wore the CSU-4/P pressure suit ensemble during a special decompression study.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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PHYSIOLOGICAL PROTECTION OF THE CSU-4/P HIGH-ALTITUDE PRESSURE SUIT

INTRODUCTION

Purpose

The CSU-4/P bladder pressure suit ensemble represents 25 years of technological advances in aerospace medical protective clothing. The crude, bulky, high-altitude pressure suit gear of the mid-1930's has slowly been replaced by lighter and more comfortable suits. This report presents and interprets the data accumulated in evaluating the physiological protection afforded by the CSU-4/P pressure suit.

Modern aircraft and space capsules lift aircrew members far above the earth's surface into the rarer atmosphere above it. The aircrewmen are normally protected from exposure to the lower pressures at high altitudes by pressurized cabins. Without such protection the airmen would suffer severe illness and even death, depending on the altitude and the duration of exposure. Currently there are operational requirements for high-altitude pressure suits to protect USAF flying personnel. Lutz (ref. 35) lists suit requirements for one type of mission. Essentially the requirements are that the pressure suit ensemble shall:

a. Offer adequate physiological protection for 5 minutes to all crew members accidentally exposed to ambient pressures as low as 33.6 mm Hg (21.4 km).

b. Be easy for the crewman to don and doff.

c. Permit the crewman to enjoy good mobility when the suit is pressurized.

d. Be comfortably cool during normal wear when unpressurized.

Background Information on Development of High Altitude Pressure Suits

Torricelli must be given credit for the first observations of the effects of reduced barometric pressures on animal life (refs. 1, 6). He was not able to determine if the deaths of animals were due to the mechanical trauma or toxicity of the mercury, or to the vacuum above the column. The Accademia del Cimento (refs. 1, 6) extended his observations. Boyle (ref. 8) perfected the vacuum pump devised by von Guericke (ref. 14) and observed that animals died when the chamber pressure was lowered sufficiently. Boyle further observed the evolution of bubbles in the aqueous humor of a viper (probably nitrogen bubbles). He probably also was the first to observe the development of water vapor and carbon dioxide in tissues exposed to extremely low pressures (6.0 mm Hg).

Previous students of low-pressure physiology have not given Boyle credit for the latter observation. Bert (ref. 6) extended these observations at low pressures and also investigated the effects of pressures greater than atmospheric. Bert clearly demonstrated that the partial pressure of oxygen is of paramount importance in supporting life at low pressures. He was well aware of the use of diving suits at greater than atmospheric pressures but neglected to suggest the use of similar suits to support life at very low pressures.

Haldane in 1920 appears to have been the first investigator to report on the theoretical value of a high-altitude pressure suit to protect humans above 40,000 feet (ref. 15).

In 1933 an American balloonist, Mr. Mark Ridge, from Dorchester, Massachusetts, wrote to Professor Haldane at Oxford University, England, seeking assistance in the development and testing of a high-altitude pressure suit. Professor Haldane referred the letter to Sir Robert H. Davis, London, for evaluation. Sir Robert began to design such a suit in the fall of 1933. Mr. Mark Ridge went abroad to England, was fitted in the suit, and was tested in the low-pressure chamber at the Siebe, Gorman Company, London, U.K. In the most severe test on 29 November 1933 (ref. 41), Mr. Ridge was protected by a suit pressure of approximately 133 mm Hg at a chamber pressure of 17 mm Hg (25.5 km) (refs. 9, 16). Mr. Ridge was apparently the first human in the world to be tested in a pressure suit in a low-pressure chamber. Mr. Ridge did not receive enough financial support for the cost of his balloon and the project was finally given up.* The Air Ministry of the United Kingdom became interested in the Haldane-Davis stratosphere flying suit. Another one was made and after a series of preliminary flights it was used by Squadron Leader F.R.D. Swain flying in a Bristol 138 aircraft tc an altitude of 49,967 feet on September 28, 1936 (refs. 9, 38, 39, 54; also see below*). In June 1937 the slightly modified suit was worn by Flight Lieutenant M.J. Adam to 53,937 feet.

While the British deserve credit for the conception of a high-altitude pressure suit and for building the first one, Mr. Wiley Post also deserves considerable note. Mr. Post desired to break the existing aircraft altitude record of 43,976 feet in September 1932, and also to enjoy the advantages of transcontinental flying above most of the weather. It is not clear if he knew about Haldane's theoretical suggestion, but in the spring of 1934 he asked his friend Jimmy Doolittle if there was an American company that might be able to make a suit. Doolittle had had favorable experience with the Research Aviation Department of B.F. Goodrich and recommended that company to Mr. Post.† The first model completed in June of 1934 was not satisfactory in chamber tests at Wright Field in Dayton, Ohio (refs. 43, 54, 55; also see below †). The second model was more satisfactory and was used during the fall of 1934 on 8 or 9 flights at Bartlesville, Oklahoma,‡ 2 flights at Chicago (ref. 42), and 5 flights at Burbank, California (ref. 42). The highest altitude he attained is not known because the two barographs failed on all but one flight. In one flight one barograph failed, and the other recorded 38,000 feet when corrected. Mr. Post was the first person to fly with a pressure suit in an aircraft, two years before the British.

The French (refs. 49, 54), Germans (refs. 50, 54, 61), Italians (ref. 54), Russians (ref. 29), and Spanish** developed high-altitude pressure suits between 1935 and 1938. All of the suits developed through 1939 were design variations applying pneumatic (gas) pressure directly to the skin surface. Such suits are called full pressure suits. There were many objectionable features to these early (gas against the skin) suits. They prevented evaporation of perspiration; they greatly reduced the subject's mobility when the suit was fully pressurized; they were heavy; they were bulky; some helmet visors glazed and fogged severely during flight.

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* *Davis, R.H., Personal Communication, March 1962.*

† *Goodrich, B.F., "Wiley Post Pressure Suit Information," Personal Communication, 1962.*

‡ *Parker, W.D., "Wiley Post Pressure Suit and Early Flights with Suit," Personal Communication, 1961-1962.*

** *NEA, W. 3rd Street, Cleveland, Ohio, Photographic Files, 1962.*

By 1939 it was well established (ref. 2) that a denitrogenated aircrewman would receive adequate physiological protection at or below 37,000 feet by breathing an appropriate oxygen-air mixture. With the advent of World War II, reconnaissance and pursuit flights up to 45,000 feet became operational requirements (refs. 30, 61). The (gas against the skin) suits were too cumbersome to be practical for such flights. A USAF physiologist named A. P. Gagge made a very important discovery early in December 1941 at Wright Field. He demonstrated that human subjects were able to survive and function more effectively for a short time at lower chamber pressures (116 mm Hg) (13.4 km) by increasing the mask pressure to 8 mm Hg pressure (ref. 10). This was the first use of positive pressure breathing at a low chamber pressure and applied the technique of positive pressure breathing first described in the German literature in 1878 by Oertel for sea level treatment of patients.

Higher mask pressures (23-30 mm Hg) allowed a brief protection and humans were abot to survive at 89 mm Hg (15.0 km) (ref. 12). This discovery by Gagge was quickly appreciated and exploited. A tremendous number of allied research medical centers studied the physiology of positive pressure breathing and attempted to improve the protection to the man (refs. 3, 4, 7, 11, 12, 17-21, 30, 40, 44-46, 52, 53; also see below*). Improvements came quickly. Gagge used a pressure vest in February 1942 (ref. 11). Canadian physiologists, Bazett and MacDougall, in October 1942 independently reported that a pneumatic waistcoat, which receives the same pressure that the mask does, enables subjects to breathe much more comfortably (refs. 4, 30). Taylor and Marbarger described a similar jacket in February 1943 (ref. 52). In March 1943, Power, Taylor, and Marbarger reported that they were able to protect a man at 87 mm Hg in such a pressure jacket and mask (ref. 44).

At the request of the U. S. National Research Council, a representative of the Canadian Associate Committee on Aviation Medical Research (Bazett) visited the Department of Physiology, University of Southern California, in April 1944. Bazett demonstrated the pressure vest and mask to J. P. Henry, research physician who was studying mechanical devices to enhance physiological protection during acceleration. Using a leg and arm counterpressure device described by Lamport et al. (refs. 22, 31-33) in addition to the Bazett vest and mask, Henry attained the low pressure of 59.5 mm Hg chamber pressure in December 1944 (ref. 17). Improvements were made in the suit and helment which enabled Henry to report successful ascents to 54 mm Hg in May 1946 (ref. 19) and to 8 mm Hg in June 1946 (ref. 21). Henry employed capstan pressure to tighten fabric on the limbs and thus deliver suitable limb counterpressure. [Jethon and Zawitkowski (ref. 27) analyzed capstan mechanics by calculus.] Subjects were able to perspire freely through the fabric on their limbs and there was less bulk on the limbs in contrast to the early gas against the skin pressure suits. Many modifications were made to the original partial pressure suit ensemble which Henry patented. Jacobs and Karstens removed the torso bladders for operational reasons (refs. 24-26, 28). Wood (refs. 58-60) added bladders to the suit described by Jacobs and Karstens, apparently unaware at the time of Henry's original work which was still classified. Mr. David Clark* and McGuire and Leary (refs. 36, 37) further modified the bladders. A singular disadvantage in fabric pressurization was the lack of thermal and immersion protection (ref. 51).

With improved materials and the knowledge gained in pressure suit design, manufacturers were finally able to produce a suit which had rubber bladders over both the torso and limbs. This bladder suit is called the CSU-4/P (refs. 13, 35).

Clark, D.M., "On Partial Pressure Suits," Unpublished Data, 1960.

EXPERIMENTAL METHOD

High-Altitude Pressure Suit Ensemble

The pressure suit which was evaluated is called "coveralls, high-altitude, type CSU-4/P" (figure 1). Prototype models no. 5 and no. 6 were used in the evaluation and may be considered to offer identical physiological protection. Prototype model no. 5 consists of a bladder tailored to cover the torso and extremities distally to the wrists and ankles. The arrangements of zippers are different on no. 6 (ref. 35).

Theoretically, bladder-type pressure suits consist of at least three layers: (a) the inner layer of bladder material adjacent to the skin or underwear, (b) the outer layer of bladder material, and (c) a top layer of retaining fabric acts to prevent ballooning when the suit is inflated. In the manufacturing process the outer layer of the bladder can be united with the top layer of retaining fabric. The MA-2 helmet was used for 80 percent of the tests and the MA-3 helmet (figure 1) was used for the remaining 20 percent. The physiological protection of these helmets is identical. Pressure gloves (figure 1) and pressure socks (figure 2) were used as described below. All subjects wore regular flying boots. An aneroid barometric pressure-sensing device was designed to detect a drop in cabin pressure. This highly reliable device would allow an increase in the oxygen pressure in the suit and helmet whenever the cabin pressure became less than 140 mm Hg. The device would maintain a fairly constant total pressure of 140 mm Hg + 5 mm Hg on the subject (suit pressure plus ambient pressure) at any chamber pressure less than 140 mm Hg. The suits were not ventilated. Oscillographic tracings were made of the decompression.

Figure 1. Coveralls, High-Altitude, Type CSU-4/P; With Helmet, High-Altitude, Type MA-3; Gloves, High-Altitude, Type MG-1; and Back-Type Parachute

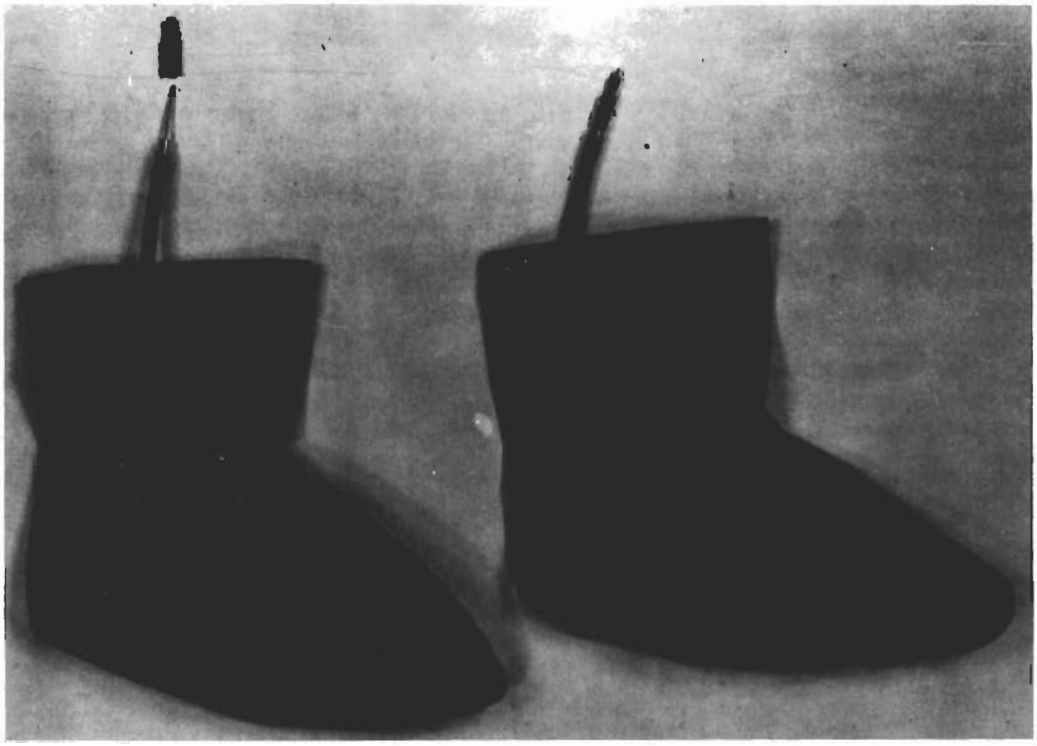

Figure 2. Experimental Pressure Socks Used for 120-Minute Tests at 8 to 3 mm Hg Chamber Pressure

Human Subjects

Fifteen human subjects participated in test profile no. 1, 14 in test profile no. 2, and 8 in test profile no. 3. All volunteers were either members of the United States Air Force or medically acceptable undergraduate students from the University of Dayton. All subjects had previous experience in evaluating high-altitude pressure suits.

Test Profiles

Each subject was fitted in an appropriate size of the pressure suit (ref. 35) and an MA-2 or MA-3 pressure helmet. Electrocardiogram leads were attached to his extremities. Communication between the subject and testing team was accomplished by earphones and a microphone in the helmet. Windows and good lighting in the low-pressure chamber allowed the research team an excellent view of each subject. Suit pressure was monitored by using a standard mercury manometer. The subject wore a B-4 parachute and sat in an ejection seat with the lap belt closed.

Test Profile No. 1

Each subject wore pressure gloves, type MG-1, in addition to the suit and helmet. Pressure socks were not worn. The subject denitrogenated on 100 percent oxygen for 30 minutes at normal atmospheric pressure, which ranged from 738 to 750 mm Hg. The chamber was evacuated to 282 mm Hg (7.6 km) in about 1 minute. At that pressure the subject made a final check of his equipment by pushing a test button which inflated his suit to a pressure of 50 mm Hg. At the end of a forced exhalation, the subject was then subjected to a rapid decompression (1.4 to 1.7 seconds) to a chamber pressure of 42 mm Hg (19.8 km), the lowest pressure to which the chamber could be automatically decompressed. The chamber was further evacuated to 33.6 mm Hg immediately. The subject remained at 33.6 mm Hg for 5 minutes while objective data and subjective remarks were recorded. After this time an additional 4 minutes was used to repressurize the subject to 141 mm Hg (12.2 km). The test was then terminated and the subject returned to normal atmospheric pressure. The subject was then examined by the medical monitor.

Test Profile No. 2

This test immediately followed test profile no. 1. The MG-1 pressure gloves were removed. The subject remained on 100 percent oxygen from the beginning of profile no. 1 until the end of profile no. 2. Pressure socks were not worn. The subject was then fitted with one leather flying glove, Type B-3A, on one hand. The other hand was unprotected. Hand selection was random. The low-pressure chamber was again rapidly evacuated to 282 mm Hg pressure. On the count of "three" at the end of a forced exhalation, the subject was again rapidly (1.4 to 1.7 seconds) decompressed to 42 mm Hg chamber pressure. The chamber was immediately evacuated to 33.6 mm Hg pressure. The subject again remained at this pressure for 5 minutes while a subjective comparison was made between the comfort of the gloved hand and the exposed hand. Then the chamber was repressurized to 141 mm Hg during a 4-minute period. This ended test profile no. 2. The subject was returned to normal atmospheric pressure and was examined by the medical monitor. Special attention was given to the hands.

Test Profile No. 3

Eight subjects wore properly fitted CSU-4/P pressure suits and either the MA-2 or MA-3 pressure helmet. The exhalation valve of both helmets was covered with a circular band of no. 60 copper mesh screen. Without this modification the exhalation valves frequently do not close quickly enough at chamber pressures less than 20 mm Hg (24.4 km) (refs. 56, 57). The slow valve action causes suit pressures to drop 10-30 mm Hg and also seriously interferes with the subject's ability to speak. All subjects wore MG-1 pressure gloves. Six subjects wore regular flying boots. Only subjects no. 1 and no. 5 wore experimental pressure socks (figure 2) inside their flying boots. Each subject denitrogenated for 2 hours at normal atmospheric pressure while breathing 100 percent oxygen. The subject entered the chamber, and the following items were checked: (a) suit and helmet hoses attached to seat kit, (b) electrocardiographic leads connected to a recording machine, (c) intercommunication connected, and (d) suit pressure checked with the test button. When preparations were complete the chamber was evacuated to 282 mm Hg in 1 minute. On the count of "three" which coincided with the end of a forced exhalation the subject was rapidly decompressed (1.4 to 1.7 seconds) to 42 mm Hg. The chamber was further evacuated as quickly as possible (usually 2 to 3 additional minutes) to a pressure of 8 mm Hg (30.6 km). The subject attempted to remain at this chamber pressure continuously for 2 hours. During this time objective data and subjective remarks were recorded. The test was arbitrarily terminated at the end of 2 hours, and the subject repressurized to normal atmospheric pressure. An examination of the subject was accomplished after the test. Special notice was given to the skin, the hands, the feet, and the tympanic membranes.

Test Profile No. 4

One subject was dressed in the CSU-4/P pressure suit, MG-1 gloves, and MA-3 helmet, and was denitrogenated at ground level for 120 minutes. The chamber was evacuated to 282 mm Hg. Five seconds before the onset of decompression the subject opened his helmet visor and raised the visor to the up-locked position as in figure 1. Three seconds before the decompression the subject began to exhale. At the moment of decompression the subject was continuing to exhale. As soon as possible after the onset of decompression the subject quickly lowered his visor and locked it in place. The following data was gathered: (a) appearance and comments of the subject, (b) suit and helmet pressures, (c) ECG tracings, and (d) the subject's reaction time. No helmet pO_2 recordings were made. The subject was decompressed three separate times, the first two decompressions occurring on the same day during the same test:

Decompression No. 1. From 282 mm Hg to 87 mm Hg in 3.2 seconds
Decompression No. 2. From 282 mm Hg to 42 mm Hg in 3.5 seconds
Decompression No. 3. From 282 mm Hg to 42 mm Hg in 1.6 seconds

RESULTS

Test Profile No. 1

Table I presents the data accumulated during test profile no. 1. It demonstrates that all 15 subjects were able to remain at 33.6 mm Hg chamber pressure for 5 minutes without any physiological impairment. All of the subjects were quite comfortable and could easily have remained at that low chamber pressure much longer. At the end of 5 minutes the chamber pressure was arbitrarily increased because of the experimental design. The pulse of the subjects (taken immediately before lowering the chamber pressure from atmospheric) ranged from 64 to 88. When pressurized as indicated in table I, the subjects uniformly experienced impaired mobility of the limbs, head, and neck. The amount of impairment was not measured objectively. The subjective opinions of these experienced subjects were unanimous. They all felt that the CSU-4/P suit, when well fitted, allowed greater ease of mobility than any of the capstan pressure suits. They all agreed that breathing was no more difficult than normally (when at atmospheric pressure wearing normal clothing). All subjects were able to successfully go through the motions of seat ejection: (a) elbows inside ejection seat, (b) feet in footrests, (c) knees together, (d) helmet against headrest, (e) hands able to reach throttle and control stick or yoke, (f) hands able to reach armrest grips and armrest triggers, and (g) hands able to reach downward ejection D-ring. There was no hand or foot discomfort in these tests. The subjects did not complain about being uncomfortably warm in the pressure suit during the 30 to 60 minutes preparation before the test. However, after decompressing the chamber to 42 mm Hg eight subjects remarked that they were pleasantly cooled over their torsos by the evaporation of accumulated perspiration. Apparently the perspiration evaporates into the low-pressure chamber by passing parallel to the skin adjacent to seams and wrinkles in the bladders. All perspiration does not evaporate—many subjects had underwear saturated with perspiration at the end of profiles 1, 2, and 3. No electrocardiographic changes were seen, except for tachycardias, when compared with records taken immediately before ascent (sitting in ejection seat in the chamber with all gear attached). There were no bradycardias or flattened T-waves.

TABLE I

PHYSIOLOGICAL DATA FROM TEST PROFILE NO. 1*

5 Minutes at 33.6 mm Hg Chamber Pressure: CSU-4/P Suit and MG-1 Pressure Gloves

Test No.	Bladder and Mask Pressure at 33.6 mm Hg Chamber Pressure (mm Hg)	Time of Rapid Decompression From 282 to 42 mm Hg (seconds)	Maximum Pulse at 33.6 mm Hg (beats/min)
1	108	1.7	120
2	110	1.6	80
3	108	1.4	134
4	108	1.5	90
5	110	1.4	100
6	110	1.5	110
7	106	1.6	100
8	112	1.7	94
9	110	1.4	88
10	108	1.5	72
11	110	1.6	76
12	110	1.4	100
13	110	1.7	110
14	108	1.7	116
15	108	1.5	100

*All subjects completed test profile no. 1. There were no signs or symptoms of dysbarism. ECG was normal for all subjects.

Figure 3 presents a representative oscillographic tracing of a decompression from 282 to 42 mm Hg in 1.4 seconds. Note that the bladder pressure promptly increases with the loss of chamber pressure. Helmet pressure briefly rises above the bladder pressure, but never exceeds 9 mm Hg pressure. The only differences in the other oscillographic tracings (see tables I, II, and III) were: (a) slight variations in the decompression time, (b) slight variations in the bladder pressure, and (c) slight variations in the mask-bladder differential pressure.

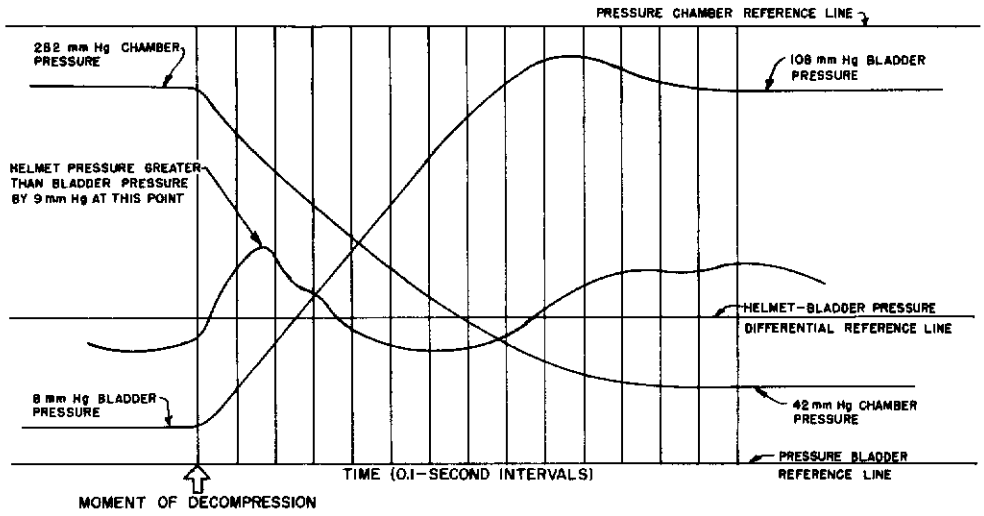

Figure 3. Rapid Decompression from 282 mm Hg (7.6 km) to 42 mm Hg (20.1 km)

TABLE II

PHYSIOLOGICAL DATA FROM TEST PROFILE NO. 2*

5 Minutes at 33.6 mm Hg Chamber Pressure: CSU-4/P Suit, B-3A Leather Glove, and Bare Hand

Test No.	Suit Pressure at 33.6 mm Hg Chamber Pressure (mm Hg)	Time of Rapid Decompression From 282 to 42 mm Hg (seconds)	Maximum Pulse (beats/min)	Remarks	
				Gloved Hand	Bare Hand
1	108	1.5	118	No Discomfort	Slight Ache
2	108	1.7	80	Slight Ache	Slight Ache
3	104	1.6	120	Slight Ache	Moderate Ache
4	106	1.6	84	Severe Ache	Severe Ache
5	110	1.4	110	No Discomfort	Slight Ache
6	108	1.4	106	No Discomfort	Slight Ache
7	106	1.4	94	Slight Ache	Slight Ache
8	108	1.7	92	Moderate Ache	Moderate Ache
9	110	1.6	76	Moderate Ache	Moderate Ache
10	110	1.5	76	No Discomfort	Slight Ache
11	106	1.4	104	No Discomfort	Slight Ache
12	108	1.5	108	Slight Ache	Moderate Ache
13	110	1.5	110	No Discomfort	Slight Ache
14	110	1.4	96	Slight Ache	Slight Ache

*All subjects completed test profile no. 2. There were no signs or symptoms of dysbarism. ECG was normal for all subjects. Petechiae were noted in every hand.

TABLE III

PHYSIOLOGICAL DATA FROM TEST PROFILE NO. 3*

120 Minutes at 8 mm Hg Chamber Pressure: CSU-4/P Suit, MG-1 Pressure Gloves, and Pressure Socks

TABLE I

PHYSIOLOGICAL DATA FROM TEST PROFILE NO. 3*

120 Minutes at 8 mm Hg Chamber Pressure: CSU-4/P Suit, MG-1 Pressure Gloves, and Pressure Socks

Test No.	Suit Pressure at 8 mm Hg Chamber Pressure (mm Hg)	Pulse Average Before Test (beats/min)	Pulse Average During 2 Hours of 8 mm Hg (beats/min)	Foot Comfort	Time of Rapid Decompression From 282 to 42 mm Hg (seconds)	Subjective Remarks on Mobility
1	140	76	88	Excellent	1.4	Fair
2	138	90	88	Fair	1.5	Fair
3	138	100	110	Fair	1.5	Poor
4	136	84	92	Fair	1.6	Good
5	140	76	90	Excellent	1.6	Good
6	142	64	76	Fair	1.5	Fair
7	140	78	72	Good	1.5	Fair
8	142	94	110	Fair	1.4	Good

*All subjects completed test profile no. 3. There were no signs or symptoms of dysbarism. ECG was normal for all subjects.

Test Profile No. 2

Table II presents the physiological data gathered during test profile no. 2. It also demonstrates that all 14 subjects were able to remain at 33.6 mm Hg chamber pressure for 5 minutes without serious physiological impairment. The only significant differences observed in this second test profile concern the hands. Some hand discomfort was experienced by each of the test subjects. Subjectively there was more discomfort in the bare hand when compared with the gloved hand in 57 percent of the subjects. The difference in discomfort between the bare hand and the gloved hand was never great.

Petechiae were noted in every hand, gloved and bare. Some subjects had a few petechiae; others had many. Petechiae reflect the high capillary pressure in the unpressurized limb. The pain was never severe enough for the subject to request termination of the test. All traces of petechiae were gone in a week in every case. In no case was there an appreciable increase in the volume of the hands. X-rays were not taken of the hands; consequently, the traces of gas recently reported at 42 mm Hg chamber pressure by the Soviets cannot be confirmed (ref. 23).

Test Profile No. 3

Table III presents the data accumulated on the subjects in test profile no. 3. All eight subjects were easily able to remain at 8 to 3 mm Hg chamber pressure for 120 continuous minutes. There were no significant differences in subjective or objective medical data when a comparison was made of the three test profiles. There was no hand discomfort. In 30-70 minutes there was tingling and numbness and mild pain in the feet of those not wearing pressure socks. The tests were arbitrarily terminated at 120 minutes in each case. All subjects stated they believed they could have continued at least 1 hour longer. Two subjects experienced some discomfort in both axillae due to pressure from the rigid inflated bladder pressing there. Both subjects were dressed in CSU-4/P suits with torso lengths that were too long. The proper torso length was not available for experimental use. In spite of the discomfort the two subjects stated they believed they could have remained at the low chamber pressure for another hour without great discomfort. With the increased suit pressure all movement was more difficult. However, with maximum effort, all of the tasks mentioned under profile no. 1 could still be accomplished, albeit with difficulty. Rare unifocal premature auricular beats were seen in one subject. Since this subject also has these beats at atmospheric pressure in the same frequency they were probably coincidental and not necessarily caused by the test procedure.

Test Profile No. 4

The significant differences between this profile and the previous ones are:

a. The subject's helmet remained open and unlocked for the following times after decompression: (1) first test, 6.5 seconds, (2) second test, 4.5 seconds, (3) third test, 5.4 seconds.

b. The subject did not appear cyanotic at any time (good view of subject, wintertime, low humidity, only slight decompression fog).

c. The subject denied any sensations of hypoxemia or impending syncope.

d. Other than a tachycardia of 140 beats per minute due to apprehension, there were no ECG changes.

e. The subject was able, in each case, to successfully lower and lock his helmet visor.

DISCUSSION

The main purpose of this study was to investigate the protection afforded to experienced human subjects who were exposed to low chamber pressures for various periods of time. All subjects were protected by the CSU-4/P high-altitude pressure suit ensemble.

This suit ensemble effectively protected all subjects without qualification whether they were exposed for 5 minutes at 33.6 mm Hg or for 2 hours at 8 to 3 mm Hg chamber pressure. The suit offers such excellent counterpressure that there were no complaints of difficulty with breathing. The earlier models of counterpressure vests, waistcoats, jerkins, and capstan-bladder pressure suits do not offer the excellence of body counterpressure afforded by suits such as the CSU-4/P and all full-pressure suits. This excellent counterpressure does not appear to significantly interfere with the normal circulation of blood or cause a shift in tissue fluids. This conjecture is supported by the normal appearance of the subjects, normal ECG (except for tachycardia), lack of syncope, and lack of subjective complaints. The tachycardia is most likely to be caused by mild hypoxia and mild apprehension. The evidence for mild hypoxia is as follows:

a. Assume a chamber pressure of 33.6 mm Hg.

b. Assume a suit pressure of 110.0 mm Hg

c. Assume an alveolar PA_{CO_2} of 35 mm Hg caused by mild hyperventilation due to mild apprehension.

d. Assume the subject has been denitrogenated for 120 minutes.

e. Assume an alveolar PA_{H_2O} of 47 mm Hg.

Since the subjects are breathing 100 percent oxygen, apply the formula:

$$PA_{O_2} = PT - (PA_{CO_2} + 47)$$

PA_{O_2} = Alveolar Oxygen Tension

PA_{CO_2} = Alveolar Carbon Dioxide Tension

PT = Total Pressure on Subject, Chamber Plus Suit

$$PA_{O_2} = 143.6 - 82 = 61.6 \text{ mm Hg}$$

With such an alveolar O_2 tension, subjects will have an arterial oxygen saturation of 92 percent (18.1 Vol % HbO_2). If the PA_{CO_2} were 30 mm Hg and the other assumptions remained unchanged, the arterial saturation would be 93 percent (18.3 Vol % HbO_2) (ref. 47).

To achieve a normal arterial oxygen saturation of 98 percent (19.6 Vol % HbO_2), it is necessary to offer a subject a PA_{O_2} of at least 103 mm Hg pressure. Solving for PT in a perfect vacuum assuming PA_{CO_2} = 35 mm Hg, then:

$$PT = PA_{O_2} + PA_{CO_2} + 47$$

$$= 103 + 35 + 47$$

$$= 185$$

In a perfect vacuum all high-altitude full-pressure suits should be pressurized with 100 percent oxygen to a pressure of at least 185 mm Hg to provide normal arterial saturation.

In some operational aircraft using capstan and jerkin pressure suits, such pressures are not feasible due to ballooning of the suit and reduced mobility. However, the state of the art is sufficiently advanced to simultaneously provide adequate arterial oxygen saturation and allow good mobility and chance for escape from the aircraft when the suit is pressurized.

During decompression the loss of chamber pressure is immediately compensated for by an increase in suit pressure during normal operation with an intact ship's supply of O_2 under pressure. Not enough facts and data are available to explain why this pressure suit responds so quickly and effectively in pressurizing a subject during and after decompression. The unavailable data is: volume change in suit during rapid decompression, temperature change during rapid decompression, volumetric flow into and out of suit during rapid decompression, and response time of F 2400 pressure suit regulator.

The feet receive adequate counterpressure during short (not over 30-70 minutes) exposures to simulated altitude (ref. 56). The unpressurized hand is often painful during 5-minute exposures to 33.6 mm Hg chamber pressure and the pain is due to the higher than normal transcapillary pressure in the unprotected hand. Pressure gloves should always be worn with any high-altitude pressure suit ensemble, despite the mission, to avoid painful hands. During the 8 tests at 120 minutes at 8 to 3 mm Hg, the experimental pressure socks provided excellent foot counterpressure and prevented foot ischemia previously reported (ref. 56).

Test profile no. 4 was incomplete and leaves many questions unanswered. It was performed without sufficient subjects or instrumentation to answer the following question: "If an astronaut or aircrewman experiences a sudden rapid decompression to an ambient pressure lower than 87 mm Hg, will he be able to close and lock his opened helmet visor before he becomes unconscious?" This very incomplete data demonstrates that it was done in one case under the highly artificial laboratory controls described above.

Test profile no. 4 represents one of a few recorded attempts to observe human performance when a subject is suddenly exposed to extremely low barometric pressures (refs. 5, 34, 48). The trend in high-altitude protective equipment is and should be toward shirtsleeve flying. An encapsulation system or detachable pod will replace the pressure suits to allow greater comfort and mobility during normal flight and to provide the escape and protective and survival gear needed in emergencies. Much research should be accomplished on human ability to react quickly and effectively in activating manual and semi-automatic encapsulation systems following a sudden rapid decompression to pressures as low as a pure vacuum.

CONCLUSIONS AND RECOMMENDATIONS

The CSU-4/P high-altitude pressure suit ensemble is a very reliable, comfortable, and physiologically effective means of protecting humans exposed to low barometric pressures for at least 120 minutes. There is every reason to believe that the duration could have been extended to 240 minutes without any suit modification (ref. 62). The physiological support offered by this suit is adequate. Arterial oxygen saturation is computed to be nearly 92 percent. When pressurized this suit allows the subject adequate mobility to execute all anticipated emergency procedures. Whenever possible pressure gloves should be worn with pressure suits to prevent mild hand pain.

When the ambient pressure approaches a near vacuum, the full pressure suit should be pressurized with 100 percent oxygen to a pressure of not less than 185 mm Hg to provide normal oxygen arterial saturation. Well controlled and carefully planned tests should be developed for studying human physiological responses during rapid decompressions to pressures between 87 and 0 mm Hg chamber pressure, while the subject attempts to close his manually operated, pressurized escape capsule.

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