The Effects of Hypoxia

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Hypoxia, a state of dysfunction due to inadequate Oxygen passing to the tissues of our bodies, has been with mankind since long before we took our first tentative leaps towards the sky.

For millennia man has travelled to and lived at altitudes where various symptoms of hypoxia would occur. Although my literature search was not extensive the first clear historical evidence of hypoxia may be found in a series of articles, published in a well-known journal of Middle Eastern origin a thousand or more years ago. One of the articles details the trip of a man who climbed to the top of a mountain where he 'saw' a bush that was burning but not actually being consumed by fire; in the flames he saw an image that he believed to be (in the quaint tribal customs of those bygone days) an angel of his god. In a subsequent article this same man claims to have spent forty days and forty nights upon that mountain (identified as being a 'Mt. Sinai') all the while not having eaten or drank. It should be clear to anyone with even the most *basic* understanding of Oxygen physiology that Moses was indeed suffering from an altered state of consciousness, very probably a semi-comatose stupor induced by *hypoxia*.

It was almost two hundred years after Acosta's [note: Jose de Acosta, a Jesuit brother living from 1540 to 1600, noted for his interest in the physical sciences) observations that man initiated ascent into our atmosphere in balloons and began to discover the dangers and limitations of altitude. The first aeronauts, a sheep, duck, cock and barometer, sent aloft in a Montgolfiere balloon from the court of Louis XVI on 19 September 1783, attained an altitude of 1,700 feet with little ill effect, excepting the cocks injured wing. The first human balloonists, following shortly thereafter, had their hands full with physical considerations such as trees, buildings, fire, and bodies of water so it wasn't until thirty years after the first manned balloon flight (on 21 November 1783, by Pilatre de Rozier and Marquis d' Arlandes, from Bois de Boulogne, Paris) that we started *'pushing the edge of the envelope'* and discovering the effects of hypoxia, decompression and hypothermia.

Soon after this first manned balloon flight an English surgeon, Dr. John Sheldon, made a balloon ascent (1784) to assess the effects of flight on the human body. Accounts indicate that he became terrified, vomited and collapsed in the balloon basket, testimony to the early mental and emotional considerations of flight.

A moment should be taken, here, to mention the discovery of Oxygen, independently in 1774 by both Joseph Priestly (England) and Carl Wilhelm Scheele (Sweden). The gas O2, with molecular weight 16.00, has since been found to be essential for the function and survival of all higher organisms. Oxygen liquefies at -182.5°C and solidifies at -223°C at sea level pressure. As balloons became capable of more lift and greater heights their human passengers started to experience a variety of altitude related symptoms. In 1793 the French balloonist Jean-Pierre Francois Blanchard commented to the American Doctor Benjamin Rush that at 9,000 m. (altitude claimed but not confirmed) blood came into his mouth and he experienced great thirst and sleepiness from the 'lightness' of the air. The much quoted balloon flight of Italians Andreoli, Brassette and Zambeccari on 7 October 1804, where all three suffered frostbite, vomiting and loss of consciousness at an altitude in excess of 15,000 ft, could well be considered the start of our experiences with aviation altitude hypoxia. Interestingly, this flight, where all aboard suffered hypoxia, occurred only *four years* after Priestly and Scheele discovered the element of Oxygen.

During the early part of the 19th century ballooning was a common enough pastime, with little apparent thought being given to the medical and physiological aspects of such flights. It was not until some eighty years after the first manned balloon ascents that attempts were made to describe the physiological changes undergone by man at altitude. Englishmen Glaisher and Coxwell made several high altitude balloon flights during the 1860s while making careful observations of the variations in their pulses, breathing, mentation, and physical coordination. During one flight, in 1862, they had almost reached 30,000ft when Glaisher lost consciousness due probably to hypoxia, and the other became partially paralysed likely from altitude decompression sickness. Fortunately they retained their wits and enough physical function to discharge some of their balloon's hydrogen and descend, suffering no long term detriment.

During the second half of the 19th century Dr. Paul Bert (1833 - 1886) was Professor of Physiology at the University of Paris. Referencing the experiences of balloonists such as Glaisher and Coxwell, as well as several mountaineers, he set about methodically evaluating the effects of altitude on human physiology. Bert's research began with observations of the demise of small animals in 'decompressed' bell jars exhausted of their atmosphere. From these initial experiments he concluded that death occurred when the *partial pressure* of Oxygen fell below 35 mm Hg, irrespective of the proportion of Oxygen in the atmosphere. It may seem almost primitively basic today, but this recognition that the partial pressure of Oxygen was paramount to survival was a major landmark in the investigation of hypoxia, not to mention the study of Aviation Medicine as a whole.

Bert subsequently built the world's first man-sized decompression chamber which, although rude by today's standards, was capable of an altitude equivalent of 36,000 ft. above sea level. In this chamber he continued experimentation on animals as well as himself. In February 1874 he spent over an hour at 16,000 ft noting the effects of hypoxia and their relief by breathing an 'Oxygen rich air' he had previously prepared. Several weeks later he was joined by Scientists Croce-Spinelli and Sivel who similarly observed and commented upon the *"…disagreeable effects of decompression and the favorable influence of super-oxygenated air ...."* at 20,000 ft.

Bert's demonstration of the beneficial effects of Oxygen at altitude prompted Croce-Spinelli and Sivel to carry Oxygen on their subsequent balloon flights, attempting to break the altitude record previously established by Glaisher and Coxwell. On their flight of 22 March 1874 they attained an altitude of 24,300 ft using Oxygen enriched air intermittently to maintain their sensibility. During a subsequent attempt to reach 26,200 ft. they took a third person (M. Gaston Tissandier) on board without increasing their already inadequate Oxygen stores. Prior to this flight they had corresponded with Bert who had presciently advised them to take much more Oxygen than they had planned. They achieved their goal, climbing to 28,200 ft., but all three lost consciousness due to the effects of hypoxia; Tissandier was the only one to waken; they had all been too hypoxemic to reach out for the Oxygen tubes that lay only a few feet away from them.

"They leap up and death seizes them, without a struggle, without suffering, as a prey fallen to it on those icy regions where an eternal silence reigns. Yes, our unhappy friends have had this strange privilege, this fatal honor, of being the first to die in the heavens" was part of Paul Bert's eulogy at the funeral of these two early altitude explorers. The two men had died of hypoxemia despite the knowledge and equipment (albeit rudimentary) being available to them for the prevention of hypoxemia.

Around twenty years after this fateful flight (4 December 1894) meteorologist Arthur Berson took a balloon successfully to 30,000 ft. using compressed Oxygen in steel flasks to prevent hypoxia.

By the year 1900, three years prior to those eventful moments at Kill Devil Hill near Kitty Hawk, North Carolina, where manned, powered and guided flight made it's faltering debut, our understanding of hypoxia was much less rudimentary than one might expect. Oxygen had been studied to no small extent in the laboratory and it was known that reducing the partial pressure of this gas below certain levels was incompatible with life. The relationship between *Oxy-Haemoglobin* saturation and Oxygen partial pressure had been explored by Paul Bert. The partial pressure of Oxygen in the air was known to be reduced at altitude. The impaired performance of balloonists at altitude was known, in part, to be due to reduced Oxygen partial pressure and methods were available to provide additional Oxygen to adventurers aloft. It had been demonstrated that sufficient altitude and insufficient Oxygen would result in the death of man. The technology was by then available to produce Oxygen rich gas mixtures and to store such gases in pressurized vessels. It would have been possible, using the technology available in 1900, to fly to around 30,000 ft. and maintain an Oxy-Haemoglobin saturation equivalent to that normally found at sea level.

It was through continued balloon flights that further understanding of hypoxia was obtained. The works of Hermann von Schrotter, a Viennese physiologist, in conjunction with Arthur Berson and Reinard Suring (both meteorology professors) expanded the knowledge of hypoxia at altitude and exposed some limitations of the preventative measures available at the turn of the century. On 31 July 1901 Suring and Berson took off in an attempt to set a new altitude record in the balloon *'Preussen'*. With them they carried compressed Oxygen which they breathed through a tube and pipe-stem mouthpiece, despite von Schrotter's recommendation that a face fitting mask should be used to assure Oxygen even if collapse occurred. The ‘Preussen’ ascended to 34,500 ft before Berson initiated descent, a timely decision as Suring collapsed soon afterwards with Berson soon following. Fortunately, both regained consciousness at around 20,000 ft. to complete their mission by landing safely.

His observations at altitude and discussion with von Schrotter allowed Suring to write authoritatively on the limits of human tolerance to altitude with and without Oxygen. One important realisation that emerged was that even 100% Oxygen would be *inadequate* for protection against hypoxia should the ascent go high enough. The calculations of Suring and von Schrotter were regrettably based on some inaccurate meteorological data, but their conclusions were nevertheless quite correct. In 1901 von Schrotter predicted that above 41,000 ft pressurised breathing equipment would be needed to maintain adequate blood oxygenation and recommended the use of pressurized, *hermetically sealed* gondolas for such high altitude sojourns.

During the first two decades of the 20th century there seems to have been great expansion and embellishment, but little original thought on aspects of hypoxia, despite great advancements in aviation science resulting from the First World War. The theories of Paul Bert and Hermann von Schrotter were used as the basis of most considerations of aviation hypoxia during the first war. It should be realised, however, that despite the development of aviation in warfare (Spanish Civil War and First World War) very few aviators during this period actually flew higher than 10,000 ft. and when they did it was for relatively short periods.

Perhaps this is an unfair statement as certainly there was a great deal of experimentation on hypoxia and much development and refinement of equipment during the first war. However, after the innovative works and theories of the likes of Bert and Schrotter the wartime progress assumes a rather mundane and repetitive nature, so it would seem.

In 1917 Barley submitted a memorandum to the British War Office detailing his observations on a variety of aircrew performance impairments that he attributed to hypoxia. He claimed that hypoxia was the cause of increased aircrew fatigue after flights at higher altitudes as well as responsible for the many reports of inappropriate or irrational aircrew actions when at altitude. He also proposed subtler degrees of impairment may develop at relatively low altitudes and opined that the relief of *all* these difficulties could be achieved by breathing Oxygen. Birley and others were aware that hypoxia was able to impair aircrew performance and a variety of experimental methods were subsequently devised in an attempt to further investigate these observations.

In Britain two researchers independently devised simple, inexpensive methods of simulating altitude exposure. One of these, the *Flack* apparatus (named after its inventor Group Captain *Martin Flack*) involved a five litre re-breathing bag (similar to a laboratory *Douglas Bag*) with a chemical CO2 scrubber. The approximate height at which hypoxic symptoms develop could be estimated by sampling the gas in the re-breathing bag at the commencement of symptoms while using the apparatus. Using the Flack apparatus a number of researchers demonstrated that some people were more resistant to the effects of hypoxia than others and concluded that selecting for these more resistant candidates would enhance the safety and performance of the Royal Flying Corps (RFC). Flack devised a number of tests that selected for the personnel more resistant to hypoxia, and these tests were in use up to the commencement of the Second World War. Flack's empirical tests were very effective in identifying people with poor respiratory responses to hypoxia but it is debatable whether rejection of these folk enhanced the performance of the RFC/RAF, owing to many other uncontrolled variables.

During the First World War there was, in Britain at least, some considerable aircrew resistance to the use of Oxygen. A variety of factors very likely played a part; for example it was considered by some to be a 'soft' or unmanly option (like parachutes, initially forbidden for RFC aviators). Others thought that shooting down an enemy while 'hiding' behind a mask was unsportsmanlike. Adding to this, the Oxygen masks of the day were almost universally uncomfortable, unreliable, and awkward to wear.

Another development in 'hypoxia technology' around this time was the invention of various *'economiser'* circuits and apparatus to reduce the proportion of wasted Oxygen in use. These Oxygen economizers (as designed by J.S. Haldane, 1917, and produced by Siebe

Gorman for use by aviators at around the same time) were initially unreliable and bulky and employed a flexible reservoir bag supplied with constant flow rate Oxygen. During inhalation Oxygen passed from the reservoir bag to the pilot's mask and when he exhaled, the bag refilled with Oxygen while his breath passed out of the mask via a one-way rubber flap valve.

Early Oxygen regulators were also somewhat rudimentary and cumbersome, not to mention unreliable. During the First World War Lt Colonel Dreyer (RFC) improved on the contemporary regulator design with its manually selected settings for certain altitudes by designing an aneroid unit that automatically adjusted the amount of Oxygen delivered as the altitude increased. Other advances in regulators at this time reflected the desirability of knowing how much Oxygen was left in the tank and how fast you were using it, hence various meters were incorporated in the basic regulator design.

The Germans had, during WWI, devised methods of controlling the rate of evaporation of liquid Oxygen and whereas British aircraft carried compressed gaseous Oxygen, the Germans were already using liquid Oxygen systems in their aircraft.

At the completion of WWI, research into hypoxia, or at least key landmarks in hypoxia research, seem to have centered once again on the ballooning fraternity. German physiologist-physician Dr. Hubertus Strughold studied previous researches into altitude physiology and began further work in the field using balloons (and later learned to fly himself).

One non-ballooning milestone at this time was the first attempt at developing a fully pressurised cabin for aircraft. It had been shown by Suring and von Schrotter that 100% Oxygen at ambient pressure would be inadequate to prevent hypoxia above a certain altitude, since determined to be approximately 40,000ft (subsequently designated the so-called ‘Armstrong Line’). While using a pressurised aircraft cabin is one method of providing Oxygen at higher than ambient pressures, another is 'pressure breathing', whereby increased Oxygen pressure (absolute and partial) is provided to the airways via a tight fitting face mask. Today we take for granted the benefits of a pressure cabin (be it sea level, 4,000 ft, 8,000 ft or other) whenever we fly in a commercial passenger transport aircraft. Among the early attempts to configure a pressurized cabin, in 1921 a wind driven pump was mounted to pressurise the cabin of a De Havilland biplane in the USA. The cabin became pressurized by this method, but in an uncontrolled manner, maintaining a 7,000 ft cabin altitude when flying at +3,000ft. This method was explored for a year or so, then appears to have been forgotten in the USA for some time (until the American XC-35 of 1939).

Post-war WWI research by the US Army Air Corps served to confirm Schrotter's predicted ceiling for open gondola balloons. In May 1927 US Army Captain Hawthorne C. Gray made further attempts on the world altitude records, using open balloons and Oxygen stored in high pressure steel cylinders. Gray reached 42,470 ft and started a descent because of hypoxia symptoms, but he then bailed out due to balloon malfunction and made a successful parachute descent. A similar attempt, six months later, found him at 42,470 ft again, commencing descent due to symptoms of hypoxia when his Oxygen supply ran out. Regrettably, he was found dead when his balloon landed.

By 1929 free balloon and aircraft ascents had been made to 32,800 ft and in 1931 German high altitude physiologist Hans Hartmann had climbed (as a mountaineer) to 28,200 ft in the Kanchenjunga region of the Nepal Himalaya without using Oxygen. These ascents further enhanced our understanding on the limitations of man in an hypoxic environment, but also suggested a capacity to adapt or acclimatize, within a certain range, to reduced Oxygen tensions at altitude.

In accordance with von Schrotter's earlier predictions, the next step in hypoxia research went hand in hand with further altitude record attempts and involved men breathing Oxygen at a pressure greater than the ambient atmospheric pressure. The concept was simple: rather than the aviators exposing themselves to the rarefied atmosphere at altitude, they would take with them an atmosphere as near as possible to that found at sea level.

On 27 May 1931 scientists Auguste Piccard and Paul Kipfer took off inside a pressurised gondola suspended from a balloon and successfully reached 51,775 ft. Piccard had designed the pressure capsule to maintain a steady sea level pressure, despite the actual altitude, and the two passengers breathed air cleansed of exhaled CO2 by an alkali 'scrubber'. Piccard's pioneering work with self-contained pressurised gondolas has since allowed man to fly to well in excess of 120,000 ft using balloons.

Meanwhile, as early as the late 1920s, Germany had recommenced work on the pressure cabin for fixed wing aircraft. In 1933 a supercharged Junkers 49 equipped with a pressure cabin successfully flew to 33,000ft and in 1936 this same plane reached 41,000ft. Similarly, France had developed pressure cabin technology by 1935, albeit with problems.

Between the First and Second World Wars, it appeared to many that that the British (and USA) had made little progress in their development of operational aircraft Oxygen systems, while it was felt, at the time, that the Germans had made considerable advances , with a consequent edge over the Allies in this respect. Little had been made of Haldane's and Siebe Gorman's Oxygen economiser equipment as can be seen in the 1932 British attempt (successful) on the fixed wing altitude record. For this flight to 43,976 ft the Bristol Aeroplane Company's test pilot, Mr. C.F. Uwins, flew the open cockpit Vickers Vesper biplane using a constant flow RAF issue Oxygen mask set to deliver 100% Oxygen. Problems experienced during the preparatory research for this flight came to the attention of Squadron Leader Gerald Struan Marshall, then Director of the RAF's Physiological Laboratory, who wrote to the Director of Medical Services pointing out the discrepancies of the Oxygen systems in use. The closing line of his report was *"…other things being equal, in a fight at over 20,000 feet, the man with the more efficient Oxygen system will win."* Within weeks research was underway on new Oxygen regulators and other equipment and over the ensuing few years the RAF Type D mask/regulator system evolved. Despite the type D mask not fully living up to expectations, it did pave the way for further advances in masks, regulators, and economisers early in the second war.

As had been previously pointed out by von Schrotter (vice supra) and Haldane *[41]* altitude exposure in excess of 33,000 ft resulted in falling arterial Oxygen saturation (Sa02), even with the use of 100% Oxygen. This had recently been overcome by Piccard using pressurised balloon gondolas and Struan Marshall's Physiological Laboratory set about developing a more portable pressurised environment, the pressure suit. In conjunction with the Siebe Gorman Company a deep sea diver's suit was modified to produce a pressure suit. During the period *1933 - 1935, this suit was developed and tested to 90,000 ft in pressure chambers.* In 1936 the suit was successfully flown to 54,000 ft, but it was found to be cumbersome, unwieldy and to have a variety of unanticipated technical and practical problems. Despite the problems at the time and its operational difficulties, that primitive suit may be clearly seen as one of the forerunners of our modern astronaut pressure suits used for intra and extra-vehicular space travel.

An American, Wiley Post, also designed and built a pressure suit in 1935. Post used this suit in 1934 and 1935 in attempting to break the trans-American speed record. [note: there is substantial historical documentation available regarding Post's pressure-suit flights, although this material has not been incorporated here]. In the mid-to-late 1930s concurrent pressure suit research was also underway in France (1935, Dr. Garsaux and Naval Surgeon Rosentiel), Italy (1937, Pezzi achieved a record altitude of over 51,000ft.) and Germany (Draegerwerke).

An interesting and somewhat amusing aside is the conclusion of some independent Russian research done during this period. In particular, one Russian researcher stated that a degree of hypoxic protection was afforded by *"...the emotional factor and the socialistic tendency of the Soviet flyer, along with physiologic compensatory mechanisms...".* The textbook quoted provides a very up-to-date (in 1939) treatise on Aviation Medicine *[46]*. Subsequent research has, however, failed to validate any degree of protection against hypoxia being afforded by devout adherence to Socialist political philosophies!

In the years immediately preceding WWII the feeling that the Allies trailed in Oxygen research prompted the decision that the development of new Oxygen supply systems should be given the highest priority in British Aviation Medical research (1939). Throughout the war research attention was concentrated upon the practicalities of Oxygen use by combat aviators. Problems addressed included how to produce and carry Oxygen, how to ensure reliable, controlled delivery of Oxygen to the aircrew, how to design a mask system that ensured the Oxygen went where it was supposed to (into the lungs) and how to minimise the effects of hypoxia during flight at high altitude.

Extensive decompression chamber examination of the efficacy of a variety of Oxygen equipment was performed at the RAF's Physiological Laboratories between 1939 and 1945. Efficaciousness of the various equipment being developed or in use was monitored by end-expiratory gas analysis on machines designed by Haldane, a laborious process to say the least, especially when the research was punctuated by alarms and everyone diving for the air-raid shelters. While there is no documentation at immediate hand of parallel research being performed in the USA, Germany, France or USSR his is to be assumed, since this series of British tests assessed a number of mask/regulator sets from Germany and USA, while France, Germany, Italy, Russia, and USA all had operational decompression chambers by the mid-1930s.

One of the findings produced during the war demonstrated potential problems for aircrew bailing out at high altitude. The work of Flight Lt Pask (RAF) in particular demonstrated the need for a 'bail-out' bottle of Oxygen if an air-crewman was to reliably survive high altitude egress from his aircraft (Barostat release parachutes were apparently not available at this time, or at least not operational).

The need for portable Oxygen systems, allowing aircrew mobility within bombers or other large aircraft was also appreciated and the precursor to the present RAF 'Loadie's bottle' was developed and designated 'Portable Oxygen Set Mark 1A'. This equipment was found deficient and a priority improvement research tasking of 1943 brought results too late to benefit operational aircrew (1945).

The problems of hypoxia in passengers was also addressed after some disastrous high altitude transatlantic flights in loaded Liberators.

Around 1940 the RAF also looked seriously at alternative forms of Oxygen storage and transport. At this time pressurised cylinders of gaseous Oxygen were generally used, liquid Oxygen (LOX) being abandoned soon after the first war due to the primitive nature of the equipment of that time (although the Germans had apparently continued using LOX). The sheer weight needed to load a non-pressurised passenger aircraft with sufficient Oxygen cylinders for a long flight made research into more efficient, lighter methods seem mandatory. One method around this weight problem was taken by researchers at the Royal Society Mond Laboratory at Cambridge who between 1939 and 1941 developed a number of machines that could produce concentrated Oxygen from the surrounding air. These machines, or *'separators'* as they were then called, worked by compressing air, allowing it to cool and liquefy, and then distilling off gaseous Oxygen by selective warming. This separator unit (popularly known as the 'ice-cream machine' at this time) was fitted to some aircraft, running off their engines, and operated effectively at 25 - 27,000 ft. Unfortunately, the promise of this equipment was not followed up to its fullest potential, partly due to weight considerations, improvements in pressure cabins and electrical equipment already making substantial demands on aircraft powerplants, until the Americans reopened research into similar *"On Board Oxygen Generator Systems (OBOGS)"* in the 1970s.

Another problem, the substantial waste of Oxygen by the systems available early in the second war was addressed by developing advanced Oxygen economisers along the lines of those previously explored by Haldane and Siebe Gorman Co around 1917 (vide supra). These *"Puffing Billy"* Economisers (*RAF Oxygen Economiser Mk. 1*) were trialed extensively throughout 1940, found to be effective above 30,000ft and to substantially reduce the amount of Oxygen (cylinders) needed for long flights. The *Mark 1 Oxygen Economiser* was pressed into service for fighter and bomber aircrew later in 1940 with the *Mark 2* to follow in March 1941. The economiser subsequently proved to be a very effective and reliable piece of equipment.

While the British were fitting all their production aircraft with Mark 2 Economisers (April 1942) the Germans and American were developing slightly different methods of 'economising' on the finite Oxygen stores that an aircraft could carry. Considerable advances were made in the design of 'demand' regulators that only permitted Oxygen to flow to the crewmember in response to his inspiratory effort (‘on demand’). The initial demand regulators displayed a considerable breathing resistance and were found tiring by aircrew, but subsequent development improved the resistance of the system. In particular, improvement to the demand valve soon made demand Oxygen systems commonplace, almost passé, in modern military aircraft.

Towards the end of the second war *acceleration atelectasis* started to become a problem for military aviators. Although not entirely appropriate to an essay on 'hypoxia', this problem was certainly potentiated by methods employed to prevent hypoxia. The pilot's symptoms of coughing and chest pain, due to closure of smaller airways in the base of the lungs due to increased acceleration (g-forces), were made worse when he had been using 100% Oxygen (as RAF aircrew had been instructed to do). The explanation behind this was provided by J. Ernsting and D. Glaister who postulated that the 100% Oxygen is absorbed from pulmonary lobules distal to the G-induced atelectatic obstruction, thus worsening the collapse: a parallel mechanism to delayed otic barotrauma.

During the war extensive RAF research effort was directed at refining the Oxygen masks being used by airmen. The RAF progressed from their Type A mask of the 1920s to the Type H-mask of 1944, which has since undergone minor improvement in its evolution to the Type

P/Q masks in use today and the Type W mask developmental mask that may see service in the near future.

Another major field of development in the prevention of hypoxia was the expansion of earlier experience and expertise in pressure cabin technology. As mentioned above the first usage of a pressure cabin occurred in the USA in the early 1920s and further developments were made by the Germans and the French during the following two decades. The French had a pressurised twin engined aircraft by 1940 that could maintain a cabin altitude of 9,700ft when flying at 30,000ft. Fuelled by Germany's successes with pressure cabins, the RAF approached the problem with some urgency in the immediate pre-war years. In 1940 the RAF had successfully pressurised their Vickers-Armstrong Wellington bomber using engine mounted compressors that could be controlled by a crewmember. 1941 and 1942 saw the incorporation of pressure cabins into RAF Spitfire fighters and Mosquito fighter-bombers used for high altitude photo-reconnaissance sorties. The Westland Welkin (looking very much like the De Havilland Mosquito) produced in 1943 was the first British aeroplane with a pressure cabin integral in its design, but did not see service before the end of the war.

The other method of preventing hypoxia at altitudes above 40,000ft is pressure breathing, as mentioned earlier. In a chronology similar to that of the pressure cabin initial, RAF research was made into pressure breathing, then shelved, only to be resurrected during WWII. In 1942 A.P. Gagge and co-workers, at Wright Field USA, developed a pressure breathing system to allow aircrew operation above 42,000ft without pressure cabins. This equipment was successful and allowed exposure to 50,000ft for several minutes without undue hypoxic problems. Canadian work on pressure breathing trailed the Americans by about a year but employed a different system, which actually provided a degree of counter pressure to the chest wall (called, by some, a pressure breathing jacket, waistcoat, or jerkin) After minor modification the Canadian equipment was teamed with a modified RAF H-mask to provide operational pressure breathing to aircrew allowing them to operate against German pressurised aircraft (e.g. the supercharged photo-reconnaissance Junkers 86) previously inaccessible to them. This equipment was flight tested to 46,000ft in 1943 and brought into service in 1944. The Americans also adopted and improved on this design (incorporating sleeves into the counter-pressure garment), later (1948) donating their improved version back to the RAF to assist ongoing research. After the second war, all high altitude military aircraft being fitted with pressure cabins and pressure breathing functioned in a '*get me down*' emergency capacity only in case of cabin pressurisation failure. Recently, however, research has indicated the benefits of pressure breathing in reducing the incidence of *Acceleration Induced Loss of Consciousness* (G-LOC) *[60]*, so much so that the USAF employs elective pressure breathing as one of the maneuvers to enhance G-tolerance in its modern jet fighter fleet and Ernsting proposes that future military aircraft Oxygen systems should employ an automatic selection of pressure breathing when certain levels of +Gz are reached.

At the outbreak of WWII full pressure suit technology was rudimentary and not sufficient to allow operational flights above 40,000ft. In 1941 the RAF rekindled its interest in pressure suits and by 1942 had test-flown one new suit. The third type of suit produced during these experiments was effective and relatively comfortable, but never actually entered service, probably due to the status of pressure cabins and pressure breathing equipment at the time. Research into full body pressure suits did, however, continue after the war fuelled by the ever-present risk of rapid (pressurized) cabin decompression and the anticipated future needs of very-high altitude air operations in which cabin pressurisation would produce an unacceptable weight penalty. Hybrids between full pressure suits and pressure jerkins were designed and in 1957 successfully chamber flown to 140,000 ft, John Ernsting himself being the ‘pilot’. Russia also had spent some considerable effort, commencing in 1934 under Dr. Vladislav A. Spasskiy, on full pressure suits and their expertise probably exceeded the rest of the world by the end of WWII, although they had done no original work on partial pressure equipment. Similarly the German Drager company was involved in developing an operational pressure suit prior to the Second World War. However, since then pressure cabin technology has continuously improved and pressure suits (full and partial) gradually saw less and less service in the RAF.

It can be seen from the above what phenomenal progress had been made in our understanding of hypoxia during the first half of this century. By the end of the second war the effects of Oxygen lack at high and very high altitude was well understood, as was the need for Oxygen administration to prevent hypoxia. The symptoms and signs of hypoxia were well recognised and documented. It had been shown, confirming previous predictions, that Oxygen at a partial pressure greater than ambient was needed to prevent hypoxia at altitudes above 40,000 ft. A wide variety of Oxygen systems had been developed around the world, variously employing high pressure gaseous Oxygen, liquid Oxygen, or generating concentrated Oxygen while in flight from the surrounding air. Equipment to protect from hypoxia had undergone great changes since the pre-WWI ‘pipe-stems’ and now there were face fitting Oxygen masks with demand regulators and non-rebreathing (or rebreathing if required) valves and regulators that automatically altered the concentration of Oxygen supplied with altitude. Pressure breathing had been developed to prevent hypoxia at altitudes in excess of 40,000 ft, as had the partial and full pressure concept suit assemblies. The greatest, single, technology advance was, in the opinion of some, the development of cabin pressurisation systems able to sustain aircrew operations at high altitude without the use of cumbersome pressure suits. Of course pressure suit technology was far from redundant and played a major role in man's subsequent confrontation with space, enabling survival and activity in that most hostile of environments.

Since around 1950 much of the development of aircraft Oxygen systems has been a matter of refining, sometimes substantially, the technology that was already available. Much work had been performed defining acceptable standards and characteristics for operation of aircraft Oxygen systems. The main exception to this generalisation being the development of molecular sieve and other *On Board Oxygen Generating Systems* (MSOGS, OBOGS), discussed further below. The development of onboard Oxygen generation systems has produced a need, in some aircraft, for devices that monitor the concentration of Oxygen in the aircraft cabin.

During these last forty years Oxygen carriage has been substantially refined with most military aircraft now carrying LOX systems with emergency backup and egress (bailout) using high pressure gaseous Oxygen. Pressure cabins have developed to the stage where many private aircraft, not just high altitude military craft or long haul passenger carriers, can be pressurised for flight at high altitude. The realisation of potential problems with rapid cabin decompression is exemplified by the fact that many jet fighter-interceptors fly at high altitude with their cabin at 18,000 ft. altitude and the pilot using Oxygen at all times, these 'low differential' cabins reduce the risk to the pilot (and therefore the mission) should the cockpit integrity be breached by missile or fragment and rapid decompression ensue. The pressure characteristics of Oxygen masks, their non-rebreathing valves and demand regulators have been detailed fastidiously. The masks and regulators have become progressively more efficient and reliable (and usually complex) employing more and more safety features. Pressure breathing, its benefits and problems, is reasonably well understood at this time and is generally available in military aircraft as an emergency 'get-me-down' facility in case of cabin decompression at altitude. The incidental discovery that pressure breathing enhances acceleration tolerance has been employed to increase pilot performance in our modern high-performance and highly agile fast jets. One result of this is that partial and full pressure suit systems have very limited application these days, the notable exception being specialist aircraft such as the U2 and SR-71 High Altitude Photo-reconnaissance aircraft whose extreme performance specifications impose special conditions on sole reliance upon cabin pressurization systems. Full body pressure suits have consequently moved into the realm of astronautics with little present day usage in (atmospheric) aviation per se. Pressure suit technology has advanced significantly as evidenced by the recent extra-vehicular sojourns of the Challenger Astronauts.

Most of the major advances in hypoxia prevention derive from various military needs and the resultant research which then tends to 'trickle down' into parallel civilian applications. The civilian Routine Passenger Transport (RPT) industry has developed some independent needs from those of military aircrew and some separate research initiatives have developed. Of particular interest here is the recent improvement in the 'quick don' Oxygen mask system for RPT aircrew and the smoke protection Oxygen hoods or masks developed to prevent incapacitation in the event of cabin fire and the release of toxic fumes from burning plastics.

Another recent variation on the hypoxia prevention theme is the Oxygen systems equipment developed for some military (and perhaps civil) maritime helicopter operations that allow some protection (albeit limited) during water submersion. This protection gives the aircrew more time, and hence, a greater chance of survival in the case of ditching and underwater egress from the cabin. The use of supplemental Oxygen to enhance night vision is also a consideration in helicopter operations.

On Board Oxygen Generation Systems (OBOGS) technology development is an important aspect in the advancement of our understanding and prevention of hypoxia that straddles the bridge between the past and the future. The concept, first developed around 1940 with the production of Oxygen 'separators', has been expanded greatly over the last 15 years and most certainly will play a major role in the development and improvement of aircraft Oxygen systems of the future. A number of OBOGS have been developed employing differing physical and chemical principles and having differing potential roles in aviation. The first method, the electrolysis of water that requires high electrical power input and carriage, and replenishment of large quantities of very pure water, has been all but abandoned. The Barium oxide/dioxide system relies on the binding of Oxygen by Barium Oxide at 540°C to form Barium Dioxide and the break-down of this compound at 900°C to release Oxygen. A usable system has been developed but high power needs and maintenance problems have made it somewhat unattractive. The electrochemical concentrator equipment uses electrical power to attract and bind Oxygen molecules to Hydrogen ions at a cathode, then release Oxygen from the resultant water molecules at a nearby anode. The system has been developed but not yet to a level acceptable for aviation usage. The Fluomine system relies on the reversible reaction of Oxygen with the Cobalt chelate, Fluomine. Tests by the USN and USAF have shown the system, in its present state, to be inadequate. Molecular Sieve Oxygen production equipment has been used for some years in hospitals but not in aircraft until recently, because of their inability to produce highly concentrated (around 100%) Oxygen. These systems employ a Zeolite filter or sieve to remove the Nitrogen from air producing a gas mixture of 95% Oxygen and 5% Argon. The innovation that allowed further concentration of the Oxygen to aviation standard (Aviator Grade, 100% pure, bone dry), was the development of a secondary Oxygen purifier in 1988. This Secondary purifier employed a Carbon Sieve to preferentially absorb the Argon from the mixture producing an

Oxygen concentration of 99.6% using electrical power; no special heating or cooling constraints apply and the systems are relatively light and compact, using engine bleed air as their Oxygen source.

Operational aircraft are already being equipped with MSOGS, most notably the USAF B1-B bomber and the USN AV-8B *Harrier* fighter. It is likely that all US military aircraft produced in the future will be equipped with advanced MSOGS as will many passenger transport jets, with continued refinement of the systems employed.

Our understanding of Hypoxia, as applied to aviation, has certainly progressed considerably from the time of the ill-fated deaths of Croce-Spinelli and Sivel to the advanced aircraft Oxygen systems of today. I hope the above information documents this progress in a sensible, sequential and understandable manner, but what now of the future? Where do we go from here? Are there, indeed, any new frontiers to conquer in the field of aviation hypoxia and its prevention?

I think so, although I find it difficult to imagine the stimulus that will drive our research to that next goal. Most probably the next series of major Oxygen system advancements will be in response to the needs of astronautics, interplanetary travel and possible extra-terrestrial colonisation. But before we consider these longer term projections perhaps we should look a little nearer to the present. What is in store for the military aviator in the next decade or so of Oxygen system advancement. I think this is well predicted by John Ernsting in his paper.

Ernsting proposes that our future combat aircraft will need an MSOGS system capable of producing near 100% (pure, dry) Oxygen at rates able to support all aircrew needs. A low differential pressure cabin will be employed with aircrew using their Oxygen system at all times. The regulator will automatically adjust the Oxygen/Air mix with altitude and induce pressure breathing at cabin altitudes in excess of 33,000ft, or upon any increase in "G" loading. The impedance to respiratory demands and mask pressure fluctuations shall be minimal and within non-tiring physical parameters. There should be 'press-to-test' facilities on the pressure breathing as well as the safety pressure options. The mask and system should incorporate or be easily compatible with NBC (Nuclear, Chemical and Biological Warfare) protective equipment. The system should have duplication of essential features, system failure warnings, simple test and emergency drill procedures, offer protection against hypoxia, drowning and suffocation upon egress from the aircraft. Bailout Oxygen and a backup Oxygen (emergency) system will employ high pressure gaseous Oxygen or staged burning 'chlorate candles'. The article goes into quite some depth and details of such a future system and is certainly worth reading.

Much of the future development in military Oxygen systems will, indeed, depend on other aircraft technology and the tactics that will be employed in future conflict. If Surface to Air Missiles became so advanced that aviation must necessarily be kept low and fast, then hypoxia prevention would no longer be a major consideration, but pressure breathing may still be attractive as a G-LOC prevention procedure. However should extreme altitudes be necessary for high atmospheric-to-space interception and penetration missions, then aviation and astronautics will again merge and aircrew may routinely use full pressure suits. As with much of past advancements, future developments in aeronautical Oxygen equipment will be driven by operational needs.

Man's extraterrestrial antics will certainly place future demands on our Oxygen technology. Prolonged extraterrestrial flight is likely in the to-too-distant future, requiring pressure cabins and suits to permit crew survival. The futuristic concept of extremely long term space flights with crew kept in suspended animation raises all sorts of new ideas about how to store, recycle, or produce de novo the gaseous Oxygen so necessary to life. Animals have already been shown to survive immersed in certain fluorocarbon liquids which carry enough Oxygen to absorb via the lungs, although breathing of hyper-oxygenated fluids is presently still fraught with many as-yet unresolved hazards. Is this the way to the future? After all, immersion of an astronaut in fluid would also protect from the dangers of extreme accelerations, so if the fluid was indeed breathable and more manageable than gaseous Oxygen, would this not appear to offer an advantage? The whole field of hypoxia research and prevention has most certainly a very, very long way to go, although I doubt that progress will be made at the rate we have witnessed during the last hundred or so years (which may only be modestly described as phenomenal).

Despite all the above consideration of astronautics there is still one aspect of hypoxia research centering a little closer to earth that needs to be addressed. This is the perplexing question of whether Santa Claus suffers hypoxia or not, and if so what can we do about it? Can an MSOGS be run from Reindeer bypass/bleed air and will we need to feed Rudolph baked-beans to increase the pressure and volume of this bypass air? As the past 100 years of aviation technology has amply evidenced, *nothing* is too preposterous to at least consider (within reason).

[NOTE: This paper appeared on the internet as part of a site associated with the Australasian Society of Aerospace Medicine. The author, apparently of English origin, remains unknown and is not identified. The nature of the information presented, although highly interesting and very readable by lay individuals, excludes citation of significant collateral aerospace medicine and life support R&D done in the United States throughout the period in reference. The paper appears to have been written in the mid-to-late 80s, as suggested by certain references, and may in fact be an academic research paper. Regardless of these considerations, it is a very interesting and comprehensive history of the effects of hypoxia on aviator aircrews up to the mid-90s. *Hypoxia* is properly defined as *an abnormally low oxygen availability to the body or an individual tissue or organ* and hypoxemia is strictly defined as *decreased partial pressure of oxygen in blood.* For a more complete understanding of the important difference between the two terms, refer to this source.

We would be most pleased to learn the identity of the author of this paper principally to assure proper credit of origin and authorship and an effort is presently ongoing to determine the latter. We hope that the appearance here of this material (for which permission to use has not been secured, reasons already explained) will be understood to be motivated solely by our sincere desire to bring useful historical information like this the public. Thank you.]