Some ergonomic assessments of the design and use of short-duration self-contained breathing apparatus

SOME ERGONOMIC ASSESSMENTS OF THE DESIGN AND USE OF SHORT DURATION SELF CONTAINED BREATHING APPARATUS

BY

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ABSTRACT

SOME EGONOMIC ASSESSMENTS OF THE DESIGN AND USE OF SHORT DURATION SELF CONTAINED BREATHING APPARATUS BY JOHN DAVIES.

The thesis is associated with the evaluation of self contained breathing apparatus designed to enable an inexperienced wearer to escape from a work area which is irrespirable due to the presence of dangerous gases or vapours, both physiological aspects and engineering performance have been considered.

The classification of both the respiratory protective devices and the hazards involved with particular reference to carbon monoxide, carbon dioxide and chlorine are stated together with the physiological factors associated with the wearing of self contained breathing apparatus of both the open and closed circuit design.

A series of pilot experiments are described including both bench testing and physiological assessment with trained subjects wearing in turn each of three open circuit and two closed circuit breathing apparatus. The resultant methods of test were also applied to a sample group of 24 inexperienced wearers over an age range of 21 to 53 years of age and the performance of facemasks, condition of inhaled air resistance to breathing duration and wearer comfort for a selected open and closed circuit design based on the pilot experiments are reported on. The investigations indicated that there was a preference for the open circuit equipment both from the method of operation and wearer comfort on the basis of the temperature of the inhaled gas.

The study also confirmed the need for care in the selection of face mask; correct fitting of the mask to the wearer and the advisability of using a well designed automatic relief valve with the closed circuit breathing equipment is most important.

The results are viewed in the context of specifications and standards and the minimum requirements that should be applied in tests for face mask leakage, resistance to breathing and general wearer use.

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My greatest debt is to my wife and family without who's encouragement and sacrifice of time and patience this work would never have been attempted, and to them it is gratefully dedicated.

QUOTATIONS

"The feeling to my lungs was not sensibly different from that of common air but I fancied that my breast felt peculiarly light and easy for some time afterwards. Who can say but that in time this pure air may become a fashionable in luxury?

Hitherto to only two mice and myself have had the privilege of breathing it".

Joseph Priestley(1774)

"A self contained breathing apparatus must suit itself to the man and his work - not the man and his work to the apparatus.

J S Haldane (1914)

"It is amazing to discover how superficial has been the analysis of the engineering aspects of the mechanics of respiration by physiologists, chemistry has seemed a more fruitful tool than physics; or more likely because the flow of air through tubes seemed too simple for serious attention, or of too little value".

Wallace O Fenn(1951)

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CHAPTER 1

BACKGROUND TO THE PROBLEM

1.1 Introduction

In the control of occupational hazards caused by breathing air contaminated with dusts,fumes,mists,uncontrolled gases,or vapours, the primary objective should be to prevent the air from becoming contaminated. This should, as far as possible be accomplished by accepted engineering control measures; although this is an idealistic approach to the problem, there will be circumstances in which for one reason or another the procedure will be uneconomical, inapplicable, impracticable, ineffective, or an emergency condition may arise due to a plant or process failure over-riding the engineering control.

Respiratory protective devices will then be needed for these situations, either as a primary means, for rescue or escape purposes or as an adjunct or supplement to other primary control measures to comply with statutory regulations.

A respiratory protective device is used to protect the wearer from the inhalation of harmful atmospheres. The protection required may be for one or more toxic contaminants or because of an atmosphere significantly deficient in oxygen. The contaminants may be in the gaseous or particulate state or a combination of both. Protection may be needed for only minutes as in a self rescue situation or for hours as in an occupational routine task.

For adequate protection against the multiplicity of conditions encountered in the present day industrial environment many types of devices have been developed. Each has a particular field of application and limitation from the viewpoint of protection as well as advantages and disadvantages from the viewpoint of operational use and maintenance.

The use of a respiratory protective device is justified only after a consideration of the factors involved indicates that the device selected will provide satisfactory protection when properly used. Therefore it is clearly evident that the selection of any respiratory device requires a thorough knowledge and assessment of such factors as the following

(i) The principles, design, scope of use, limitations, advantages and disadvantages of the respiratory protective device under consideration.

(ii) The chemical, physical and toxicological properties of the substances against which protection is required.

(iii) The nature of the duties to be performed by the wearer of the protective devices particularly as they relate to restriction of movement and physiological demands.

1.2 Classification of Respiratory Protective Devices In order to promote greater uniformity in the naming of the various devices available on the market and to provide a basis for a clear understanding of the operating principles and uses of the devices implied by the name, the British Standards Institute have published BS.4275 Recommendation for -"The selection, use and maintenance of respiratory protective equipment," and have also promoted standard definitions and classifications for respiratory protective devices. Appendix A lists these definitions as well as terms used in the respirator field. The following British Standards also deal with devices for protection against harmful dusts and gases.

BS.2091 Specification for respirators for protection against harmful dusts and gases.

BS.4555 Specification for high efficiency dust respirators.

BS.4558 Specification for positive pressure powered dust respirators.

BS.4667 Specification for Breathing Apparatus.

part 1 - Closed Circuit breathing apparatus.

part 2 - Open circuit breathing apparatus.

part 3 - Fresh air hose and compressed air line breathing apparatus.

There is at present no British Standard that deals with apparatus designed only for escape purposes which is the topic of this research work.

1.3 Classification of Respiratory Hazards The purpose of this section is to outline a classification of respiratory hazards and to detail the toxic effect of three possible industrial gaseous hazards namely Carbon monoxide, Carbon dioxide, and Chlorine.

Toxic materials can enter the body in three ways, through the gastro intestinal tract; through the skin or through the lungs. Of these three modes of entry, the human respiratory system presents the quickest and most direct avenue of entry because of its intimate association with the circulatory system and the constant need to oxygenate tissue cells.

There are two basic respiratory hazards

(i) Oxygen deficient air

(ii) Air laden with contaminants

The normal constitution of air at sea level and normal barometer pressure of 760 mm. mercury is shown in the following table:-

Gas	%
Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Carbon dioxide	0.035(variable)
Neon	0.00182
Helium	0.00052
Krypton	0.00011
Hydrogen	0.0001
Nitrous oxide	0.00005
Xenon	0.000009
Ozone	0 - 0.000005

Oxygen concentrations below 16% will not support combustion and are considered unsafe for human exposure because of harmful effects on bodily functions, mental processes and co-ordination. At low oxygen conditions collapse can be immediate and death can ensue within minutes. While 16% oxygen at sea level is generally considered the lower limit for safe human exposure, the partial pressure of oxygen within the lungs is the important factor. Of the work which has been done on oxygen toxicity Paul Bert (1878) observed convulsive seizures in animals exposed to high oxygen pressure and reported that the higher the pressure the shorter was the time required to produce convulsions. The first report of man suffering an oxygen convulsion was made by Thompson (1935) who described the experience of two divers breathing pure oxygen at a pressure of 3040 mm Hg (4 atmospheres) Haldane (1941) experienced a sudden and violent convulsion with little

warning when breathing oxygen at 5320 mm Hg (7 atmospheres) for 5 minutes.

Bean (1948) studied all the available reports, summed up the evidence both in man and animals and presented a full account of the problem. Donald (1947) as a result of a large series of experiments on man was able to give a clear picture of the clinical aspects of oxygen poisoning, the predisposing factors and the variability of reaction, this report also established limits of tolerance which are now generally accepted in diving practice.

Air contaminants include particulate matter in the form of discrete particles of solids or liquids, and aerosol material in the form of a true gas or vapour or a combination of both gaseous and particulate matter.

Particulate contaminants can be classified according to their physical and chemical characteristics and their biological effect on the body.

A useful classification of their physical characteristic is as follows:-

Dust - Mechanically generated solid particulate matter (found in the harmful size range of form 0.5 to 10 microns).

Mist and Fog - Liquid mechanically produced particulate matter (with sizes generally in the visible or macroscopic range).

Fumes - Solid condensation particules of fine diameter commonly generated from molten metal as metal fumes,(size range from 0.1 to 1.0 microns).

Smoke - A system which includes the products of incomplete combustion of organic substances in the form of solid and liquid particle(size from 0.01 to 0.3)and gaseous products in air. It is usually of sufficient concentration to perceptibly obscure vision.

Living Organisms - Airborn bacteria and virus(usually found in the size range from 0.001 to 15 microns).

The particle size in microns is of utmost importance. Particles below 10 microns have a greater opportunity to enter the respiratory system and particles below 5 microns are apt to be retained in alveolar spaces. In a healthy individual particles from 5 to 10 microns can generally be removed from the respiratory system by the cleansing action of the ciliated epithelium in the upper respiratory tract. The efficiency of the cleansing action is markedly reduced in diseased systems or it may be overwhelmed by excessive exposure.

The fate of particulates which reach the deep lung or alveolar spaces depends upon their solubility, particle size, chemical characteristics, and metabolism in the human body.
The biological effects can be classified as follows.

Inert Aerosols Those which only produce minor irritation or discomfort although in sufficient quantity can overwhelm the protective mechanism of the upper respiratory tract.

Allergy Producers Those which cause severe sensitivity reactions with some individuals.

Chemical Irritants Those which damage the sensitive mucous membranes or lung tissue by chemical action.

Fibrosis Producers Those which cause the development of scar tissue in the lung such as silicosis from mine dust exposure and asbestosis from exposure to asbestos.

Carcinoma Producers Such as asbestos, chromates and radioactive particulates which produce cancer in some individuals after "latent" periods of 20 - 40 years.

Systemic Poisons Such as lead cadmium arsenic, which can damage certain critical organs and systems.

Febrile Reaction Producers Such as the fumes containing zinc and copper which produce chills followed by fever.

Gaseous contaminants or vapours from organic liquids can likewise be classified according to their chemical characteristics and biological effect on the body as follows.

Inert Gases such as nitrogen, helium, argon, and neon which do not metabolise in the body but as a dilutant may produce an oxygen deficiency by displacement of air.

Acidic Gases Such as carbon dioxide, sulphur dioxide, hydrogen sulfide, hydrogen chloride, which are acids or produce acids by reaction with water. They taste sour and many are corrosive to tissue.

Alkaline Gases Such as ammonia, phosphine arsine which are alkalis or produce alkalis by reaction with water. They taste bitter and many are corrosive to tissue.

Organic Compound Are compounds of carbon which can exist as true gases or vapours from organic liquids, for example saturated hydrocarbons(methane,ethane,butane) unsaturated hydrocarbons(ethylene and acetylene) alcohols, ketones,isocyanates,epoxies,and aromatics.

Organometallic Compounds - Comprising metals attached to organic groups such as tetraethyl lead and organic phosphates.

Gaseous contaminats can also be classified according to their biological effects as follows:-

Simple Asphyxiants Physiologically inert substances which interfere with the uptake, transport or utilisation of oxygen in the body such as nitrogen, methane, and hydrogen by creating an oxygen deficiency by air displacement.

Chemical Asphyxiants Such as carbon monoxide which in low concentrations interfere with the uptake and transport of oxygen by the haemoglobin of the red blood cells or hydrogen cyanide which oxidises the cell tissue.

Chemical Irritants Those acid or alkali gases which irritate the respiratory system and cause the development of pulmonary oedema or fluid in the lung.

Anesthetics Cause loss of feeling and sensation with unconsciousness and possible death for example nitrous oxide hydrocarbons and ethers. Some anesthetics injure body organs for example carbon tetrachloride(liver and kidneys)chloroform(liver and heart)benzene (bone marrow)and carbon disulphide(nervous system).

Systemic Poisons Those which can damage critical organs and systems of the body such as metallic mercury vapour, hydrogen sulphide and arsine.

The degree of effect of both gaseous and particulate contaminants depends largely upon the airborne concentration and the degree of exposure. The Department of Employment (DEP)publish annually a listing of Threshold Limit Values(T.L.Vs) as a guide for exposure concentration which a healthy individual normally can tolerate for an 8 hour day 5 days a week without harmful effects. Airborne particulate concentration are generally listed as milligrams per cubic metre of air (mg/m^3) and gaseous concentrations are listed as parts per million(ppm)by volume.

1.3.1 Specific Hazards - Carbon monoxide It is not normally present in the atmosphere but results generally from the incomplete combustion of carbonaceous materials. It is frequently found in the industrial environment produced from a wide variety of processes and conditions, and has been a toxicological problem to man throughout his history.

It is colourless and odourless and it is therefore most insidious in its action. Table 1.1 based on the work of Shulte(1964) gives a guide in summarised form to the symptoms following an exposure to various concentrations of carbon monoxide and also the correlation between % of carbon monoxide in air concentration and blood levels. It must be emphasised that these figures are approximate only and would not be reliable if the individuals were breathing a mixture with a reduced oxygen content or containing other contaminants. It also applies to sea level atmosphere and not to atmospheres at reduced or increased pressure. There is also some individual variation in susceptibility to carbon

monoxide and therefore the statements in tables such as this cannot be precise, but must be used as a general guide.

CO in Air (ppm)	COHb (%)	Symptoms
100	10 - 20	Tightness across the forehead, possibly slight headache, dilation of the cutaneous blood vessels.
200	20 - 30	Headache and throbbing in the temples.
300	30 - 40	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting, and collapse
500	40 - 50	Same as above, a greater possibility of collapse, syncope and increased pulse and respiratory rates.
750	50 - 60	Syncope, increased respiratory and pulse rates, coma, intermittent convulsions, and Cheyne-Stokes respiration.
1,000	60 - 70	Coma, intermittent convulsions, depressed heart action and respiratory rate and possible death.
1,500	70 - 80	Weak pulse, slow respirations, respiratory failure, and death within a few hours.
2,000	80 - 90	Death in less than an hour.
4,000	90 +	Death within a few minutes.

TABLE 1.1 CO in Air %CO Hb and resutling symptoms

Carbon monoxide has an affinity for the haemoglobin of the blood Haldane (1895) attributed the harmful and often fatal effects of this gas to its greater affinity for haemoglobin compared to oxygen, forming the stable compound carboxyhaemoglobin in the red blood corpuscles. The % of this in the blood represents a direct measurement of the reduced oxygen carrying capacity. Douglas et al (1912) reported that the addition carboxyhaemoglobin altered the disassociation curve of the remaining oxyhaemoglobin impeding oxygen release to the tissue, this was the first indication that carbon monoxide was not an inert gas.

Due to a greater respiratory exchange of air contaminated with carbon monoxide the haemoglobin of an individual performing physical work attains its equilibrium concentration of carbon monoxide in a shorter time than that of a resting individual and symptoms appear faster. As exercises also involves an increased demand for oxygen by the active tissues any deprivation of oxygen carrying capacity is also felt more severely than when at rest.

The maximum permissible concentration in the atmosphere to which persons may be exposed for a working day of 8 hours is set at a Threshold Limit Value of 50 ppm DEP(1971).

1.3.2 Carbon Dioxide A normal respirable atmosphere contains 0.035% carbon dioxide. The concentration of carbon dioxide in alveolar air is approximately 5-7%. This increase in alveolar air as compared to that of normal atmosphere air is due to gaseous diffusion of carbon dioxide from the pulmonary capillary bed.

If the concentration of carbon dioxide in the inspired air increases the ratio of alveolar to capillary carbon dioxide decreases and becomes progressively more unfavourable for normal diffusion of carbon dioxide from the blood. The body will compensate for this alteration in diffusion rate by an increase in respiratory depth and rate with an accompanying increase in cardiac output. If the carbon dioxide in the breathing atmosphere continues to increase, the increase in cardiac and respiratory ratio cannot effectively compensate, and carbon dioxide will accumulate in the blood and other body tissue.

The following Table 1.2 gives a guide to the relationship between % carbon dioxide in air, the depth and rate of ventilation and effect.

$\%CO_2$ in Air	Depth of Ventilation ml.	Frequency/ min	Effect
0.04	673	14	
0.79	739	14	
2.02	864	15	Headache and dyspnea on mild exertion
3.07	1,216	15	Headache severe diffused sweating dyspnea at rest
5.14	1,771	19	Mental depression
6.02	2,104	27	Visual disturbances and tremors develop

TABLE 1.2 Effect of increase CO_2 concentration

Since the rate of production of carbon dioxide by man is approximately 75% of his rate of utilisation of oxygen, the air will attain a concentration of 3% carbon dioxide at about the same time that the level of oxygen has been reduced to 17%.

It is clear therefore that the carbon dioxide content of the inspired air in a closed circuit apparatus should not be allowed to reach values that have an significant effect on the minute volume. This is particularly important with open circuit types of apparatus as the effective duration of the respirable air supply will be reduced. A reasonable criterion based on such pertinent data as is available is that a concentration of carbon dioxide equivalent to 1% should be regarded as the maximum allowable in self contained breathing apparatus during the specified period of effective duration, this concentration will increase the minute volume by 6 to 7%.

The factors which govern the control of carbon dioxide content in the design of breathing apparatus, are the effective dead space, the performance of valves and in the case of closed circuit apparatus the

chemical efficiency of the absorbent cannister. These are dealt with in detail in the subsequent chapter.

In the industrial environment the maximum permissible concentration in the atmosphere to which persons may be exposed for a working day of 8 hours is set at a Threshold Limit Value of 5,000 ppm DEP(1971).

1.3.3 Carbon monoxide/Carbon dioxide mixtures Carbon dioxide at low concentration (1-2%) act as a stimulant to both rate and depth of respiration. The effect of increasing the carbon dioxide concentration of the ambient air is to increase the alveolar concentration of carbon dioxide and the body reacts by attempting to wash out this excess carbon dioxide by increasing the depth and rate of respiration.

More carbon monoxide will therefore be absorbed in unit time if the air breathed contains a mixture of carbon monoxide and carbon dioxide than if air containing only carbon monoxide is inhaled because of the increased volume of air passing through the lungs. It would appear therefore that there is no justification in reducing the T.L.V. for carbon monoxide in air in the presence of carbon dioxide. DEP Technical Data Note 2/71 states that special considerations should be given also to the application of the TLVs in assessing the health hazards which may be associated with exposures of two or more substances. A brief discussion is also included of basic considerations involved in developing TLVs for mixtures, and methods for their development is amplified by specific examples.

1.3.4 Chlorine is widely used in industry in the paper, textile, and power generation industries, in the maturing of flour, in the sterilisation of water and in the manufacture of many organic and inorganic products.

There is a risk of exposure to chlorine both in its manufacture and use. It may also be liberated when solutions of hypochlorites such as bleaching powder or some other common disinfecting agents, are unintentionally allowed to come into contact with acids.

It is a pungent and irritating gas which causes pulmonary irritation and oedema. It can be recognised by smell in concentrations of about 4 parts by volume per million of air. It is an acute irritant to the mucous membranes of the eye nose and respiratory passages. The symptoms of over exposure including cough and bronchospasm, appear immediately and bronchitis may continue for some days. A more severe effect, not often encountered in accidental over-exposure is the delayed development of pulmonary oedema which may appear up to two days after the over exposure. Apart from an asphyxial state it may leave residual lung damage of a crippling nature, and obviously a man with an already established respiratory disease is at a greater risk than the normal Cotes (1969).

Table 1.3 gives some idea of the effect of significant concentrations. M.O.L. (1966)..

Concentration of Chlorine in Air		Effects
ppm (v/v)	mg/m^3 (20^oC)	
1	3	None.
4	12	Slight smarting of the eyes and irritation of the nose and throat
10	29	Severe coughing and eye irritation within one minute.
GREATER THAN 10	GREATER THAN 29	Effects immediate and if delayed may be serious

TABLE 1.3 Chlorine in Air and resulting symptoms

The maximum permissible concentration in the atmosphere to which persons may be exposed for a working day of 8 hours is set at a Threshold Limit Value of 1 ppm DEP(1971).

1.3.5 Summary of the Respiratory Hazards

Proper and adequate assessment of the hazard is the first important step to protection in assessing the overall hazard potential consideration should be given to possible emergency conditions which can arise in order to ensure that proper emergency control equipment and procedures are both available to and thoroughly understood by potentially effected personnel.

The following Table 1.4 gives the number of cases of Carbon monoxide, carbon dioxide and chlorine poisoning reported by the Factory Inspectorate over the past decade.

	GASES					
	Carbon Monoxide		Carbon Dioxide		Chlorine	
	Fatal	Total	Fatal	Total	Fatal	Total
1961	8	73	3	8	-	21
1962	12	102	-	2	-	45
1963	3	75	-	1	-	38
1964	5	76	-	4	-	65
1965	4	68	-	2	-	79
1966	1	72	-	4	-	65
1967	10	66	-	2	2	71
1968	3	77	1	4	-	78
1969	3	59	-	5	-	52
1970	6	63	6	63	-	87
1971	4	5	-	1	-	44

TABLE 1.4 Gassing accidents analysed by nature of gas 1961 - 1971.

1.4 Physiological Factors The purpose of this section is to describe the physiological factors which must be considered in respiratory protection, and to discuss those physical factors that must be considered in the design testing and use of self contained breathing apparatus. It is not intended to cover the mechanism of oxygen transport through the pulmonary membrane, as this subject has been reviewed in adequate detail in many textbooks of human physiology.

For the work at present under review the lungs have been considered to be inflatable elastic bags in which the inflation is created by the downward movement of the diaphragm. The flow of air entering the lungs through the nose or mouth into the oral nasal cavity and thence through the trachea into its sub divisions the bronchi and into the smallest receptacles of the lungs, the alveoli. The important point to be emphasised here is that inhalation is an active movement created by a nervous impulse to the phrenic nerve which innervates the diaphragm and causes it to contract downwards decreasing the intrathoracic pressure relative to the external atmosphere which inflates the lungs. During inhalation oxygen transport takes place through the pulmonary epithelial membrane to the blood circulating through the lungs, coincidentally there is a simultaneous passage of carbon dioxide into the alveoli. During exhalation which is largely passive except under 'forced conditions' the diaphragm relaxes. By means of this relaxation the chest cavity returns to atmospheric pressure and may move to increased intrathoracic pressure and the lungs deflate through elastic collapse expelling the air through the same airway system.

It must be noted that both inhalation and exhalation can be augmented by such accessory activity as movement of the ribcage, by the external and internal intercostal muscles, shifts in posture of the thoracic spine and elevation or collapse of the ribcage by actions of the arms.

When breathing through a respiratory device the important consideration is that inhalation is a physiologically active action, exhalation being passive, the resultant movement of air being a concommittant oscillation of pressure relative to environmental atmospheric pressure. A major factor in the use of respiratory protective devices is therefore the resistance which they offer to the respiratory cycle and thus interfere with the pressure oscillation. The lung function is designed primarily for gaseous exchange and involves a two phase system (i) a gas phase on one side of the membranes and (ii) a liquid or blood phase on the other. It has been noted that it is also necessary for consideration to be given to the influence of respiration resistance and physical work of breathing on other factors, ie the cardiac system anatomically speaking, is also in the lung cage because of forced breathing in either phase stress can be placed upon the system. Fortunately these effects will occur at resistance of values far higher than those which the subjects of this investigation will be expected to tolerate.

1.4.1 Definition of Terms

Within this study only the following physiological factors important in respiration were considered in any detail, minute volume, mean inspirating flow, instantaneous air flow, tidal volume, inspiratory and expiratory resistance to air flow and respiratory work rate.

Minute Volume The minute volume is the volume of air in litres breathed per minute by a subject. This may be measured during inhalation or exhalation. There being very little difference between the two values, as the depletion of oxygen during inhalation is compensated for by volume of carbon dioxide and water vapour from the metabolism of the body.

Minute volumes for adults vary from a minimum of about 5 litres for subjects under basal conditions of complete rest to about 100 litres

at heavy work rates. Table 1.5 indicates average values measured at 20°C for a number of work rates, the primary purpose of this table was for general consideration in the estimating and evaluating of flows which self contained breathing apparatus may be required to accommodate.

Mean Inspiratory Flow The concept that the average inspiratory flow rate is twice the numerical value of the minute volume for working conditions has been accepted for this work and has been used as the basis of resistance measurements in the experimental work.

Instantaneous air flow These flows are important in the design of self contained breathing apparatus as they determine the velocity of air through the various components ie demand valves, absorbent canisters; breathing tubes, exhalation valves etc.

Tidal Volume A value of some importance in physiological response to resistance is the tidal volume, the volume of air breathed per breath.

1.4.2 Effects of Resistance versus Air Flow A survey of the literature reveals that the effect on respirators of added resistance to breathing have been investigated in many ways.

Changes in the parameters mentioned above, minute volume tidal volume and also respiratory frequency; respiratory level; oxygen uptake; oxygen extraction factor; carbon dioxide output; carbon dioxide percentage in expired air respiratory quotation; alveolar partial pressure of oxygen and carbon dioxide; oxygen content and capacity and pH of the blood; pulse rate; blood pressure; cardiac output; cardiac stroke volume; and electrocardiogram have been reported.

Necropsy findings on experimental animals have also been described.

Silverman et.al(1945) reported that after a full review of the literature little quantitative and positive information on the effect of

Measurement	Seden-tary	Work Rate, mkg min							
		0	208	415	622	830	1,107	1,384	1,660
Subjects	29	12	12	14	12	59	46	8	6
Pulse rate per minute	73	93	105	116	128	158	166	177	178
Respiration rate per minute	14.6	19.6	21.2	22.7	23.0	30.4	34.8	40.7	47.6
Minute volume,liters	10.3	14.2	20.8	29.9	37.3	54.7	75.3	104.0	113.8
Maximum inspiratory flow,l/min	40	49	63	84	100	149	194	254	286
Maximum expiratory flow,l/min	32	43	58	85	107	154	211	314	322
(Maximun inspiratory flow/(minute volume)	3.9	3.4	3.1	2.8	2.7	2.7	2.6	2.4	2.5
(Maximum expiratory flow)/(minute volume)	3.1	3.0	2.8	2.9	2.9	2.8	2.8	3.0	2.8
(Maximum inspiratory flow)/ (maximum expiratory flow)	1.3	1.1	1.1	1.0	1.0	1.0	0.9	0.8	0.9
(Inspiratory cycle)/(total cycle),%	39.2	41.4	44.1	46.8	48.2	48.3	49.4	51.3	50.2
(Expiratory cycle)/(total cycle),%	57.6	58.2	55.8	53.2	51.7	51.6	50.6	48.7	49.8
(Rise)/(inspiratory cycle),%	17.7	20.7	16.3	13.3	13.8	11.2	14.3	16.9	18.2
(Sustained flow)/(inspiratory cycle),%	58.7	59.0	65.3	69.4	65.9	71.1	69.8	68.1	68.0
(Maximum flow occurrence)/ (expiratory cycle),%	27.7	37.5	47.9	46.8	46.7	45.1	44.0	44.4	50.4
(Rise)/(expiratory cycle),%	11.8	20.3	23.5	21.6	22.3	18.8	19.0	21.1	21.8
(Sustained flow)/(expiratory cycle),%	49.3	37.4	51.0	52.3	53.1	57.7	59.7	57.1	61.3
Oxygen deficit,%	3.56[b]	3.89	4.30	4.41	4.63	4.31	4.12	3.39	3.44
Oxygen consumption,ml/min	306	496	800	1176	1545	2075	2723	3114	3413
Carbon dioxide production,ml/min	261	425	695	1068	1432	2017	2723	3399	3598
Respiratory quotient	0.85	0.86	0.87	0.91	0.93	0.97	1.00	1.09	1.06

a. Resistances were 6 mm of water inspiratory and 3 mm expiratory.
b. Values from 11 subjects are included in the mean values for gas analyses.

TABLE 1.5 Mean air flow measurements and Gas Analysis for nine levels of activity

(reproduced from Respiratory Protective Devices Manual)(1963))

moderate resistances on the respiration and circulation had been reported and carried out a large series of experiments of 55 young healthy adult males. A large number of different resistances were used in the experimental work.

In Campbell's (1957) experiments an added resistance to expiration caused a rise in the respiratory level. Cain & Otis (1949) reported a slight rise in the pressure of carbon dioxide and fall in the pressure of oxygen in the alveolar air of 5 subjects at rest breathing against a resistance. They estimated the work done against the resistance and also the corresponding extra consumption of the subjects. They also found that the inspiratory muscles were almost twice as efficient as the expiratory.

Cooper (1960) suggested methods of testing and standards of resistance for respiratory Protective devices.

Senneck (1962) made a comparison between various resistance standards and suggested that an ideal standard for closed circuit breathing apparatus inspiratory work rate in mkg./min should be as shown in the following table

Minute Volume	Senneck	Cooper	Cotes (1962)	
			Lamin.	Turbulent
10	0.08	0.63	0.15	0.05
30	0.51	1.88	0.66	0.62
50	1.5	3.1	0.7	1.1
100	7.4	6.3	(2.0)	6.4

It is therefore concluded that the rate of respiratory work done on a breathing apparatus is the parameter most likely to be of use in assessing resistance. It is probable that if the inspiratory resistance is less than the expiratory the intrathoracic pressure will be more positive than

normal. Thus the ratio of inspiratory to expiratory work will give a satisfactory indication of the overall effect of the resistance on the mean intrathoracic pressure. It is likely that any derangement of this may be responsible for many of the physiological ill effects of breathing against a resistance.

The conclusions from the Silverman work can conveniently be summarised as follows:-

1. Added external resistance tends to cause a reduction in minute volume and frequency of respiration. Physiological mechanisms can apparently compensate for large changes in resistance.
2. When the expiratory resistance is greater than the inspiratory the oxygen uptake is reduced. Addition to inspiratory resistance so that it becomes larger than the expiratory restores the oxygen uptake.
3. There is subjective discomfort if the inspiratory resistance is less than the expiratory and both are greater than 50 mm H_2O at 85 l/min.
4. With resistance less than 106 inspiration 53 expiration the discomfort is related more to the ratio than the total resistance.
5. The effect on resistance is less marked in those trained to physical work or respiratory resistance.

In considerations of the possible parameters which may be of use for the definition of allowable limits of resistance Silverman and his co-workers stated the following. "A limit on external respiratory work appears to be the best basis for stating tolerable limits of resistance" and discussed the limits that might be imposed. The following investigations after Silverman's work into the effect of breathing against resistance have also been reported.

The reduction in minute volume due to added resistance has been confirmed by Cain and Otis (1949) Di Giorgio & Giulio(1950)Giulio

(1950-1951) and Morrow and Vosteen (1952-53).

Di Giorgio and Guilio also claimed that the playing of a stream of cool air on the face of subjects breathing against resistance increased their minute volume.

McIlroy et.al.(1956) reported that resistance caused a reduction in frequency of respiration and a simultaneous rise in respiratory level.

Estimates of the work done in each phase provide an index to the effect of the resistance on intrathoracic pressure. This argument is pursued in Chapter 2 with a view to establishing the behaviour of various types of breathing apparatus are compared.

1.5 Self-Contained Breathing Apparatus is defined in BS.4667 as an apparatus using a supply of air or oxygen from a cylinder or other container which is an integral part of the apparatus.

There are two types

(a) Open-circuit type - Compressed air carried in cylinders is fed through a demand valve and breathing tube to a full facepiece. Exhaled air passes through a non-return valve to the atmosphere.

(b) Closed circuit type apparatus in which the exhaled air is re-breathed by the wearer after the carbon dioxide concentration has been effectively reduced and the oxygen concentration enriched. It is used either with a full facepiece or with mouthpiece and noseclip.

The self contained breathing apparatus has it is claimed no limitations as to the concentration of gaseous or particulate contaminats in which it may be worn. Since the wearer of such an equipment carries his own supply of respirable atmosphere with him this therefore is the obvious first choice of a suitable respirator protection device for self rescue purposes under an emergency condition ie. from an atmosphere dangerous

to life the concentration and contaminate being an unknown quantity.

The chief limitation of this type of apparatus is the duration of protection it affords and the possibility of inward leakage which may occur around the facial seal.

The problems of designing breathing apparatus for self rescue purposes is firstly the question of mechanical construction and secondly the physiological factors.

An open circuit type apparatus will basically consist of a

(i) Full vision mask fitted with exhalent valve.

(ii) Demand Valve.

(iii) Breath Tube.

(iv) Valved high pressure Compressed Air cylinder fitted with pressure gauge.

(v) Means of supporting the equipment while wearing.

The physiological burden that this type of apparatus presents to the wearer is the resistance offered by the demand and exhalation valves,weight to carry limitation of vision and restricted movement.

A closed circuit type apparatus will basically consist of

(i) Full vision mask.

(ii) Breathing tube.

(iii) Breathing bag(counterlung)fitted with automatic relief valve.

(iv) Valved High pressure oxygen cylinder fitted with pressure gauge.

(v) Flow control device.

(vi) Cannister for carbon dioxide absorbent.

(vii) Means of supporting the equipment while wearing.

The physiological burden that this type of equipment presents to the wearer is the resistance offered by the breathing circuit, the temperature and humidity of the inspired gas, and the concentration of carbon dioxide in the closed circuit, weight to carry, limitation of vision, and restricted movement.

In any examination of the physiology factors of a breathing apparatus laboratory studies under controlled conditions are considered the prerequisite Cooper(1967). For such work a mechanical breathing machine can be used which simulates human respiration and with which the chemical and thermal loads applied to the apparatus may be varied to correspond with different work rates. It is emphasised however that since breathing apparatus and wearer must function as a single unit the ultimate appraisal of the equipment must clearly depend on the results of practical tests made with wearers under conditions comparable with those to be experienced in use.

1.5.1 Facemask Design As previously mentioned the point at which the apparatus will present the most likely problem is the seal between the facemask and the wearer's face. This section considers those factors which should be considered in the design for facepieces which completely encloses the wearers face including eyes, nose, mouth and chin.

Faces have been classified according to the general appearance of the full face as round, square, or triangular and then subclassified within the system eg. variation of the round include vertical, oval and horizontal oval. Attempts have also been made to identify faces according to profile as concave convex or straight. The configuration of current facemask design are not intended for any particular face type, they appear to represent a designers concept of a face piece which will

best fit the largest number of people - "the universal fit".

As previously stated the effectiveness of breathing apparatus is dependant on a number of mechanical devices namely demand and exhalation valves, these assemblies if mounted on the facemask require openings which become potential points of penetration for the ambient atmosphere, therefore the seal at these points should be effective for the life of the equipment and the mounting should be capable of withstanding a certain amount of roughhandling without developing points of leakage.

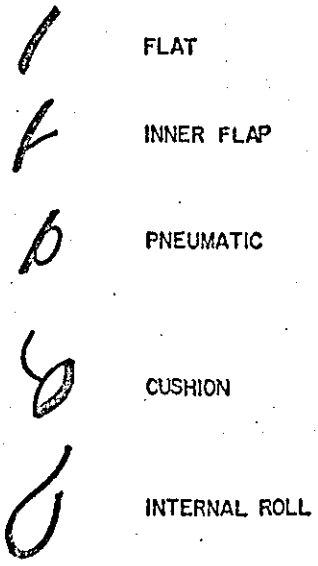


Figure 1.1 Respirator facial seal designs.

Figure 1.1 shows cross sections of the peripheries of several facepieces in current use. Jordan (1963) has described the characteristics of these peripheral seal designs and the difficulties in achieving a good fit. Burgess and Hinds (1970) reported variations in leakage between masks at low sealing forces due to flexibility of the individual facepieces and the resulting ability of the masks to contour to the facial form. The flat and inner flap seals were probably the most effective mask in this regard. The pneumatic seal had a well defined form but required greater

force to permit continuous facial contact and a pillow pressure of 0.75 p.s.i.g. was required on many subjects before the pneumatic cuff was roughly contoured to the face. Griffin and Longson (1971) reported on the superiority of the pneumatic seal type of mask compared to the plain seal mask.

Lack of flexibility in the facemask and the periphery makes it difficult for the facepiece to contact facial contours. Quite often therefore the tension needed to seal all points on the periphery results in excess pressure at certain spots causing pain in sensitive areas.

1.5.2 Facemask Suspension Ideally a facemask should be held against the wearers face by an infinite number of adjustable supports to direct tension where needed. Practically a proper seal can be achieved with six adjustable straps attached at six symmetrical points around the periphery of the facemask. Adjustment of this number of straps is not too complicated but for unaccustomed wearers adjustment should be of a positive nature and an elasticated self adjusting head harness would assist the effectiveness of facial seal. Five adjustable straps on a full facemask appears to be the minimum number to ensure a seal.

The buckles on head harnesses should be easily adjustable by pulling on the individual straps and should retain that adjustment without slippage. Ideally they should be attached to mouldings in the rubber, although some facemasks buckle straps are fastened to the facemask with metal rivets. Tension on the buckle strap may distort the rivet hole. When full facemasks are worn for extended periods hard facial pressure from the metal rivet heads on a restricted area of the face or head may create painful areas and make continued use of the facemask intolerable.

1.5.3 Valves Both inhalation and exhalation valve assemblies Figs.1,2, 1.3, 1.4 Pages 54, 55 and 56 may be mounted on the facemask and care should be taken to ensure that these are mounted in the ideal position to permit ideal flow balance of the facemask, and unrestricted vision.

1.5.4 Communication The ability to communicate while wearing a respirator can affect both the wearers comfort and the usefulness of the respirator. Communication may make the difference between a safe efficient operation and confusion and panic where control over a situation is imperative. Speech transmission through a facemask is extremely difficult and irritating to the wearer as well as fatiguing and inexperienced wearers have been known to insert a finger and pull the mask away from the face in order to communicate. Ernstrong and Gabb (1961) have reported fully on this problem and Siegal et al(1955)established criteria for evaluating speech transmission through full facemask.

A well designed speech diaphragm placed in the facemask assists materially speech transmission and may be combined in the exhalation of inhalation valve assemblies, with the added advantage of low price and easier instrumentation for radio communication.

1.5.5 Dead Space:- The term "dead space" when applied to a full facemask can mean either the geometric dead space which is the volume between the mask and the wearers face or the "effective" dead space which is a measure of the exhaled breath rebreathed by the wearer: A measure of the geometric dead space can be determined by measuring the volume of water required to fill the space between a mask and a dummy head. A measure of the effective dead space which is a more realistic evaluation requires a more complicated technique and details of such a test have been reported by Griffin and Longson - (1971). Fig.1.5 to 1.10 Pages 57,58,59,60,61 and 62 inclusive also show Xray cross section of six typical facemasks.

British Standard BS4667 also states that the carbon dioxide concentration breathed by the wearer of a breathing apparatus shall not exceed an average of 1%. Therefore at a tidal volume of 2 litres the dead space of full facemasks should not be greater than 400 cu.cm. On closed circuit breathing apparatus slip from the purifier may increase the carbon dioxide concentration, dead space of facemasks for this type of equipment should have a lower volume.

1.5.6 Visual Limitations Any facemask affects the wearers ability to see. The adverse effect may be due to, reduced total field of vision, distorted field of vision or misting of the visor or eyepieces. Upward and downward vision as well as sideward vision is of utmost importance under emergency conditions. Ability to see the safest pathway or stairs to see and avoid low hanging pipes and supports and to recognise without delay any motion or situation at the extreme sideward limit of normal vision is often the key to satisfactory handling of a critical situation.

Diminishing vision in a facemask may be caused by the attachment of various components. As stated previously respiratory protective equipment is used under actual or potential emergency conditions and the wearers ability to see may determine his response to the situation; any diminution of the normal binocular field of vision with impaired depth perception could have serious consequences. Trained wearers of equipment may be able to adapt themselves to lack of depth perception but people wearing this equipment for the first time under emergency conditions may respond to a sense of uneasiness from the lack of depth perception. Therefore a facepiece allowing greater binocular vision even though the total field of vision is somewhat reduced, should be preferred to monocular eyepieces.

Minor scratches and opacities although annoying to a wearer and resulting in a minor loss of visual acuity can be managed, usually the annoyance is not extreme. Impaired vision from misting however is intolerable. This may occur when water in warm humid air condenses on the outside of a cold visor this can however be wiped. If the visor becomes misted on the inside due to an ambient temperature differential to the facemask internal this presents an acute problem. Anti-dimming compounds or soap have a limited effect and condensation from some types of closed circuit apparatus is sufficient to wash the film from the visor. An ori-nasal inner mask arranged such that the breathing circuit is contained within this area minimises misting in closed circuit equipment. On open circuit equipment facemasks fitted with an ori nasal inner mask arranged such that on inhalation the air is drawn through a duct which directs the air over the surface of the visor before entering the nose cup through non-return valves have also been used successfully. Permanent coating of the visor also merits some consideration.

1.5.7 Skin Compatability The materials used for facemask mouldings should contain no additives that could be skin sensitizers. Generally only elastomers proved harmless are used, but occasionally an individual may be unduly sensitive to one or some of the ingredients used in compounding rubber.

1.5.8 Wearability A wearers comfort and acceptance of the distress which may be caused by the facemask are of no less importance than the effectiveness of the equipment separating him from an irrespirable atmosphere "Comfort" cannot really be expected from a device that restricts vision, breathing and ventilation and may put him at some risk due to inward leakage. There is again no relationship between discomfort and effectiveness. Individuals will always experience some discomfort when

wearing a respiratory device the distress should however be minimised.

Conclusion as previously stated on page 16 there is at present no British Standard that deals with apparatus designed only for escape purposes. This type of apparatus is being classified as one which will enable a wearer to escape from a work area which is normally safe but which may have become irrespirable due to the presence of dangerous gases or vapours. It is essential to emphasise that this type of equipment may be expected to be worn by inexperienced people of either sex from an age range of 18 to 65 years.

Based on the foregoing observation the following are some suggested design and performance standards that this type of apparatus should meet.

1.6 Suggested Specification for short duration breathing apparatus

(a) The apparatus should be self contained of either the closed or open circuit type.

(b) Method of operation

(i) Open circuit compressed air breathing should be designed and constructed to enable the wearer to breathe air on demand from high pressure air cylinders via a demand valve, exhaled air passing from a full face mask via a non-return outlet valve.

(ii) Closed circuit breathing apparatus should be designed so that the exhaled air of the wearer passes from a full face mask through a breathing tube into a purifier containing chemicals which absorb the exhaled carbon dioxide. Oxygen being fed into the breathing circuit from a cylinder of compressed oxygen. This oxygen and purified exhaled gases should mix in a breathing bag

(counter lung) and be fed back to the wearer via the breathing tube connected to the face mask, any excess volume of gas should be released through a relief valve.

(c) Materials All materials used in the construction should be fire resistant where practicable. Exposed parts of the apparatus should not be made of materials which on impact are liable to give rise to frictional sparks capable of igniting flammable gas mixtures. Materials that may come into contact with the skin shall be non staining, soft pliable and shall not contain known dermatitic substances.

The apparatus shall be sufficiently robust to withstand the usage it is likely to receive in service. The design and construction should permit the component parts to be readily separated for cleaning, examination and testing and after reassembley shall be gas-tight. All parts requiring manipulation by the wearer should be kept to a minimum and be readily accessible and easily distinguishable by touch in darkness.

(d) Face mask should be designed to meet the following requirements, it should cover the eyes, nose, mouth and chin and should provide adequate sealing in the face of the wearer from the external atmosphere, whether the skin is dry or moist, when the head is moved, and when the wearer is speaking.

A head harness should hold the facemask firmly and comfortably to fit against the contours of the face so that the inward leakage is limited to a value of not more than 0.01%. The weight should be symmetrically balanced to ensure the maximum retention of the

facial seal and minimise muscular strain. Vision restriction should be kept to a minimum. Any hose of tubing connected to the face mask should be flexible, should permit free head movement and should not restrict, restrain or close off the air supply as a result of any bodily movements.

(e) Gas Cylinders Should comply with Home Office Specification T if fitted with operating valve this should comply with BS 341 Part 2.

(f) Condition of inhaled air Carbon dioxide content of the inhaled air(including dead space effects) should not exceed 2.0% by volume during the use of the apparatus.

(g) Temperature of inhaled air should not exceed 40^{o}C.

(h) Resistance to Breathing Neither the inspiratory nor the expiratory side of the apparatus should have a dynamic resistance greater than 50 mm H_2O.

(i) Duration The effective duration of protection of the apparatus should be 10-15 minutes based on a respiratory rate of 40 litres/min.

(j) Comfort A wearer should not show any undue signs of strain attributable to wearing the apparatus and should be impeded as little as possible in facilitating an escape.

Prior to the Experimental work a number of breathing apparatus manufacturers were approached and requested to supply equipments for evaluation based on the foregoing specification. Five equipments(3 open circuit and 2 closed circuit)were submitted by three manufacturers and the following assessment was made.

1.7 Description of breathing apparatus used in the experimental work

(A) Closed Circuit Apparatus.

1.7.1 Equipment. Code Nos OX.1 Figures 1.9,1.11 & 1.12 Pg.61 63 & 64 was a closed circuit self contained breathing apparatus using a pendulum breathing action and comprised a full vision flat seal rubber face mask with a single non-kink rubber breathing tube connected to a plastic breathing bag.

A small oxygen cylinder with a constant reading pressure gauge and flow control device supplies oxygen to the breathing circuit for a minimum duration of fifteen minutes. The initial flow into the closed system being claimed at 7 litres/min. A 6.5 litre breathing bag was fitted with an automatic relief valve, a cylindrical 'purifying' canister containing a carbon dioxide absorbent was positioned within this bag.

These components were coupled to a carrying frame with a simple neck strap which supported the total weight of the apparatus.

1.7.2 Technical Appraisal. The lightweight drawn steel cylinder complied with Home Office Specification T was fitted with a specially designed cylinder valve. The flow control unit gave a 9 litre initial flow of oxygen (manufacturers claimed 7 litre) which adequately flushed the breathing circuit supplying the wearer with a high concentration of oxygen, the excess oxygen was released through the automatic tandem control unit was based on a capillary flow principle and had no moving parts. The pressure gauge was coupled to the cylinder and gave a direct reading of the cylinder content by a zoned colour code calibration.

The 'purifying'canister was cylindrical in shape and held an average of 430 grammes of 8-12 mesh absorbent granules,

these being retained by gauzes at the top and bottom of the cylinder with circlips.

The canister was charged and emptied by removing a screw plug situated at the side of the canister and access to this was by removal of the relief valve in the bottom of the breathing bag.

The face mask made of rubber gave complete facial protection with a flat facial seal. It had fitted a removable moulded perspex vizor. A six point elasticated head suspension harness held the mask to the face.

The 30 mm breathing tube of non-kink rubber was secured to the mask and breathing bag by worm drive hose clips.

Evaluation of this equipments performance had not been reported on outside of the manufacturers literature. Table 1.6 summarises the manufacturers technical specification.

1.7.3 Equipment Code No,OX.2 Figures 1.10, 1.13 and 1.14 Pg.62,65 & 66 was a closed circuit self contained breathing apparatus using a constant flow lung demand breathing circuit.

The apparatus was contained in an impact resistant plastic container and comprised of a high pressure oxygen storage cylinder coupled with a cylinder valve and constant flow lung demand regulator, a breathing bag with presssure relief valve, and a corrugated breathing tube connecting the breathing bag to a flexible full face mask.

The apparatus is carried in a sling position under the arm with adjustable facility to bring the apparatus easily into a chest position for wearing.

1.7.4 Technical Appraisal The apparatus was of continental manufacture.

The carrying case was subdivided internally into a 'purifying' container and a cylinder holder. The absorbent cover

which extended over the bottom of the case was fitted with two non-return valves for controlling the flow in the breathing circuit, connections for the breathing bag and the corrugated breathing tube. The container held 600 grammes of absorbent granules which was retained between gauzes at the top and bottom with a tension spring and lock ring. The filling of the container required the use of special tools and equipment. The breathing bag was made of rubberised fabric and had a capacity of 4.5 litres; fitted to the breathing bag was a pressure relief valve in the form of a double valve, the inner valve was made of mica the outer was a rocker valve with rubber seal, this could also be operated manually.

The lightweight drawn steel cylinder complied with Home Office Specification T was fitted with a combined cylinder valve and pressure gauge which gave a direct reading of the cylinder content by a zoned colour code calibration. Fitted directly on to the cylinder valve was a lung demand/constant flow control unit which comprised a miniature pressure reducer and constant dosage unit set at 1.5 litres/min flow rate, a manually operated rocker arm enabled the wearer to bypass the constant flow device. A 20 mm breathing tube connected the absorbent container cover to a flexible full face mask.

The face mask body was vulcanised in one piece and was sub-divided into a nose mouth area and an eye area by means of an inner mask giving a very small dead space. The material was 1 mm. elastic rubber and facial seal was obtained by a moulded inner flap suspension was by one fixed and 4 infinitely adjustable straps. Two oval splinter-proof removable eye pieces were clamped to the face mask.

This equipment was by way of a prototype in so far as the full face mask was being used for the first time. The breathing circuit with 1 litre per minute constant flow using mouth piece and nose clip had been evaluated by Cretin(1967) and using 1.2 litre per minute constant flow by Steinkohlenbergbauverein(1967) Table 1.6 summarises the manufacturing technical specification.

		OX.1	OX.2
Weight fully charged	Kg	2.7	2.4
Breathing bag capacity	l	6.5	4
Cylinder capacity	l	40	45
Flow rate initial	l/min	7	1.5
Absorbent Charge	g	430	600
Static Resistance in	mmH_2O	20	17
ex	"	20	25
Charging pressure	bar	198	200
Duration	min.	15	30

TABLE 1.6 Technical Specification as supplied by manufacturer for OX.1 and OX.2 equipments.

(B) Open Circuit Apparatus

1.7.5 Equipment Code No.CA.1 Fig.1.2,1.6 and 1.15 Pg 54,58 & 67 was an open circuit self contained breathing apparatus using a demand valve breathing system. The apparatus comprised a full vision face mask with a large bore non-kink low pressure breathing tube connected to a demand valve mounted direct on to a drawn steel compressed air cylinder fitted with a constant reading pressure gauge. Two exhalation valves opening to atmosphere were fitted either side

of the breathing tube on the face mask. A 50 mm wide sling woven terylene harness was attached between the demand valve assembly and the cylinder which supported the total weight of the equipment.

1.7.6 Technical Appraisal The drawn steel cylinder complied with Home Office Specification T and contained 400 litres of compressed air at a working pressure of 193 bar. The contents of the cylinder was indicated by a pressure gauge with zoned colour code calibration. The demand valve assembly was of the tilt valve design and was an integral part of the cylinder assembly being secured onto the cylinder assembly by screw thread, and locked in position by a nylon faced grub screw. The rubber face mask was of the full vision type and incorporated an air cushion face seal, head suspension was by six elasticated head strips. The exhalation valve assemblies were of the rubber mushroom type.

The apparatus was entirely automatic in use this being accomplished by using the demand valve assembly in place of the conventional cylinder valve. When the wearer placed the mask to his face and inhales the resulting slight negative pressure is transmitted from the face mask down the large bore breathing hose and onto the demand valve. The demand valve diaphragm moves under the differential pressure across it and operates the tilt valve which opens and allows air from the cylinder to pass up the tube and on into the face mask to the wearer. As soon as the wearers demand is satisfied the pressure equalises in the mask, breathing tube and demand valve, the diaphragm moves back and the tilt valve closes, the exhaled air passes to atmosphere via the exhalation valve assemblies. The equipment was worn in the shoulder slung position.

1.7.7 Equipment Code No.CA.2 Fig 1,3,1.7,1.16 and 1.17 Pg.55,59, 68 & 69 was an open circuit self contained breathing apparatus using a demand valve breathing system with a pressure reducer. The apparatus comprised a full vision face mask fitted with demand and exhalation valve

assemblies, the demand valve being coupled to pressure reducer assembly mounted onto a valved drawn steel compressed air cylinder which was fitted with a constant reading pressure gauge. A 50 mm wide woven terylene harness was attached between the cylinder valve and cylinder which supported the total weight of the equipment.

1.7.8 Technical Appraisal The drawn steel cylinder complied with Home Office Specification T and contained 400 litres of compressed air at a working pressure of 193 bar. The cylinder valve complying with BS 341 part 2 'C' had a two-way body which screwed directly into the top of the cylinder. Opening and closing of the valve was effected by means of a handwheel, clockwise rotation closing and anti-clockwise rotation opening the valve. The outlet side of the valve was coupled to a pressure reducing valve which reduced the cylinder pressure to 7 bar. Tapped into the reducing valve was a constant reading pressure gauge with zoned colour code calibration. A small bore supply hose screwed into the outlet side of the reducing valve and was coupled at the other end to the demand valve assembly.

The demand valve comprised a circular stainless steel body and a thin rubber diaphragm which was retained in position by a cover and spring clip. Secured to the inside of the body and bearing upon the diaphragm was a spring loaded lever which operates a pin return inlet valve. A screwed coupling was swaged in the rear of the valve body to facilitate connection to the full face mask.

The full face mask was of moulded rubber and had a self inflated rubber cushion face seal. Head suspension was facilitated by one fixed and four adjustable rubber straps. A full clear view visor was clamped to the face mask the demand and exhalation valve

assemblies were fitted to the face mask, the exhalation valve assembly was of the rubber mushroom type.

The method of operation required the opening of the cylinder valve, the donning of the face mask after which the functioning of the apparatus was the same as that described for CA.1 equipment.

The equipment was worn in the shoulder slung position.

1.7.9 Equipment Code CA.3 Fig 1.4,1.8 and 1.18 Pg 56,60 & 70 was an open circuit self contained breathing apparatus using a high pressure demand valve breathing system. The apparatus comprised a full vision face mask fitted with demand and exhalation valve assemblies, the demand valve being coupled to a drawn steel compressed air valved cylinder by a rigid high pressure hose. A 25 mm nylon woven webbing was connected to base and neck of the cylinder, the apparatus being worn across the body suspended from the neck.

1.7.10 Technical Appraisal The drawn steel cylinder complied with Home Office Specification'T' and contained 400 litres of compressed air at 193 bar. The cylinder valve complied with BS 341 part 2 type "B" had a two way body which screwed directly into the top of the cylinder opening and closing the valve was affected by means of a hand wheel clockwise rotation closing and anticlockwise rotation opening the valve. The outlet side of the valve was coupled to a high pressure rigid hose the other end of the hose being coupled to the demand valve assembly.

The demand valve consisted of a nylon seated tilt valve held on its seat in a brass valve body by the cylinder air pressure. The valve was centralised by a conical spring compressed by a screw collar sliding on the valve stem this spring also served to diffuse the air as it entered the valve casing. The tilt valve was sealed into a black nylon case with an 'O' ring and secured by two self

tapping screws. The tilt valve projected up into the case and the large moulded rubber diaphragm which operated it was clamped in position by a front cover. The diaphragm carried at its centre a stretched silk speech diaphragm mounted on a fibre ring bonded to the rubber. Mounted on the front cover of the demand valve assembly was a flow adjuster hand screw which when rotated operated the tilt valve to give an infinitely variable constant flow to the face mask 3 screws secured the demand valve to the face mask.

The full face mask was of moulded rubber and incorporated a foam plastic filled cushion to effect the facial seal. The visor was formed from toughened perspex and was permanently bonded into a groove in the mask. The head suspension was by a combined single moulding of six adjustable rubber straps. The mask was finished with three internally moulded bosses on in the centre for the demand valve assembly and the right hand boss carried the exhalation valve assembly. The third boss would be used for a telephone microphone if required. The exhalation valve was of the simple non-return type consisting of a rubber mushroom with associated sealing mounted in an adaptor.

The method of operation required the opening of the cylinder valve the donning of the face mask after which the functioning of the apparatus was the same as that described for the CA.1 equipment. The equipment was worn in the across body slung from neck position. No content pressure gauge was fitted by the manufacturer.

Technical specifications as supplied by the manufacturers is shown in Table 1. 7.

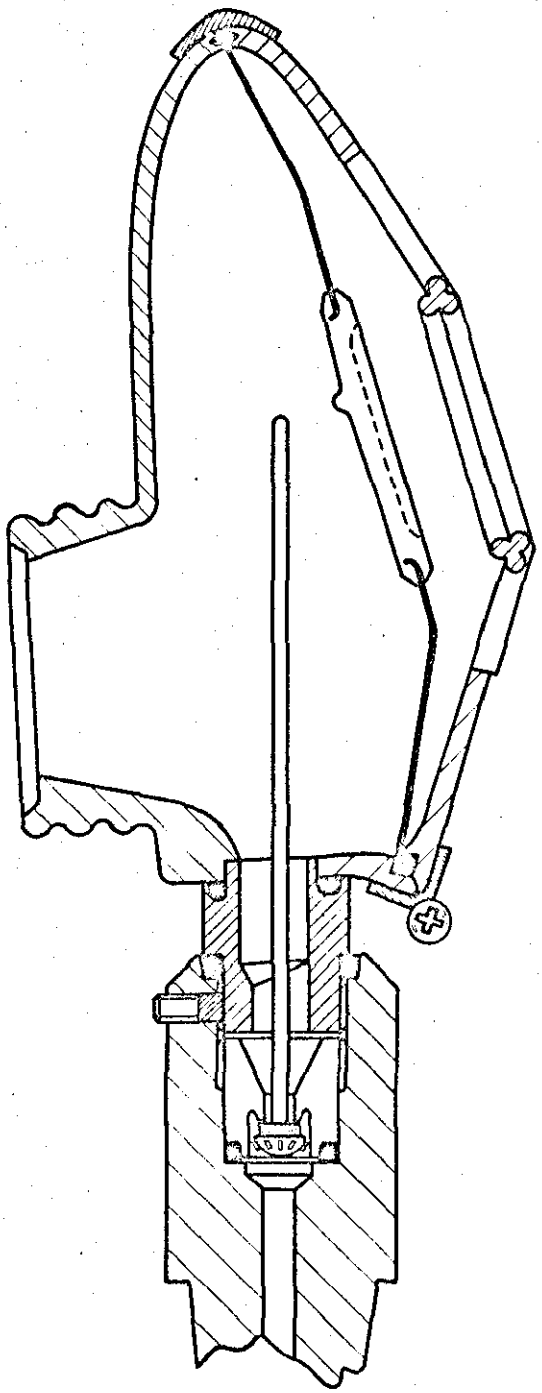
		CA.1	CA.2	CA.3
Weight fully charged	Kg	4	5.6	5
Cylinder capacity	1	400	400	400
Static resistance in	mmH_2O	35	12	42
ex	"	10	8	6
Charging pressure	bar	193	193	193
Duration	min	10	10	10

TABLE 1.7 Technical Specification as supplied by manufacturers for CA.1, 2 & 3 equipments

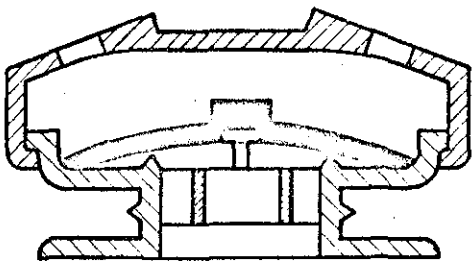
1.7.11 Summary

All the closed and open circuit equipments could in general terms be said to comply with the requirements for Method of operation and materials used in the construction of the equipments as specified in Section 1.6.

The suggested performance requirements for facemask, conditions of inhaled air, resistance to breathing, duration and wearer comfort were investigated and form the basis of Chapter 2 of this work.

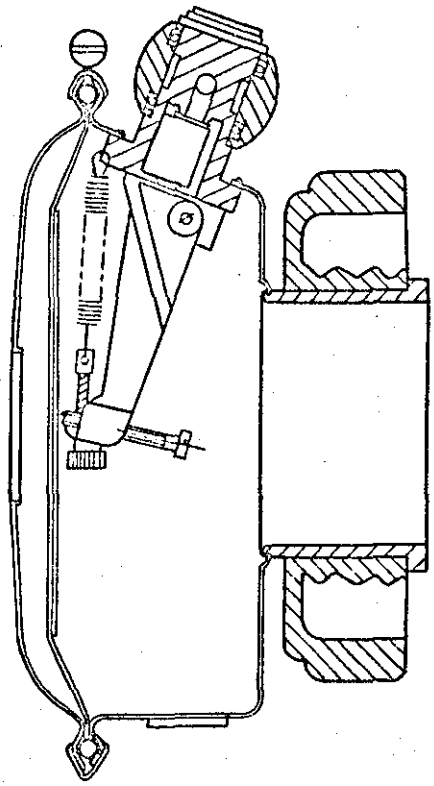


DEMAND VALVE.



EXHALATION VALVE.

C.E.G.B.	S.E. REGION
GENERAL ASSEMBLY OF DEMAND VALVE AND EXHALATION VALVE C.A.I.	
st. ISSUE A 2.7.72	Fig. 1.2 — S.E.R. 632/2



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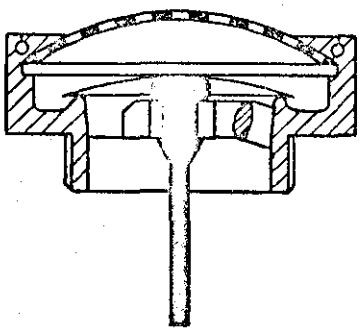
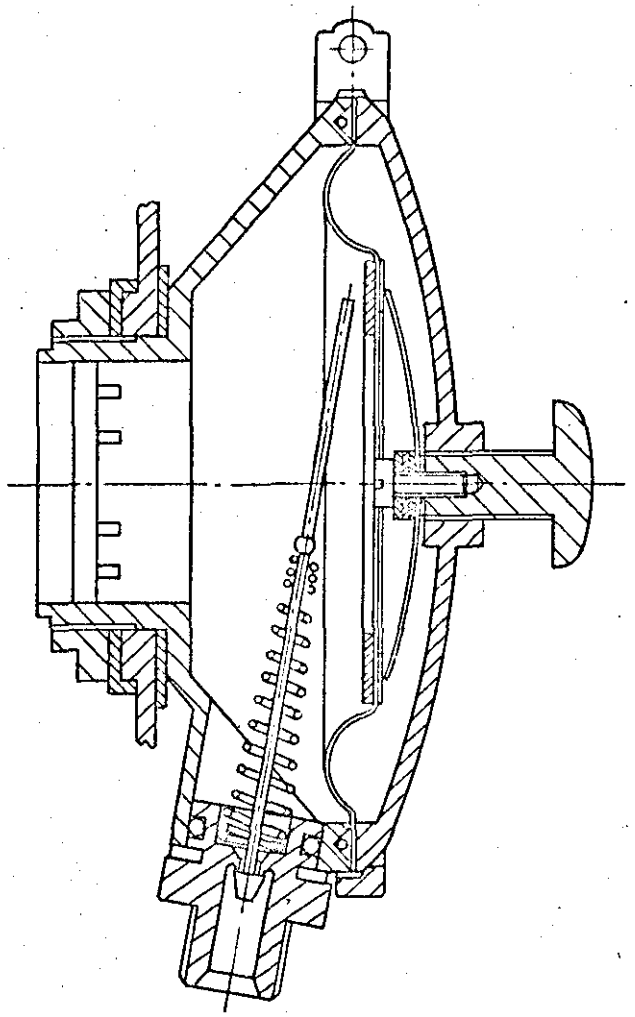


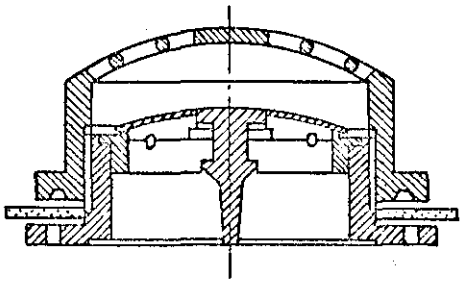
EXHALATION VALVE

C.E.G.B	S.E. REGION
GENERAL ASSEMBLY OF DEMAND VALVE AND EXHALATION VALVE C.A.2	

st. ISSUE	A			
10. 7. 72.			Fig. 1.3	SER 632/3



DEMAND VALVE



EXHALATION VALVE

C.E.G.B.	S.E. REGION
GENERAL ASSEMBLY OF DEMAND VALVE AND EXHALATION VALVE C.A.3	
Fig. 1.4	SER 632/5

st.ISSUE	A	
10.7.72.		

FIG No 1.5 X-Ray Cross Section

Face Mask Assembly CA 1

2

FIG No 1.6 X-Ray Cross Section

Face Mask Assembly CA 1 Modified Visor

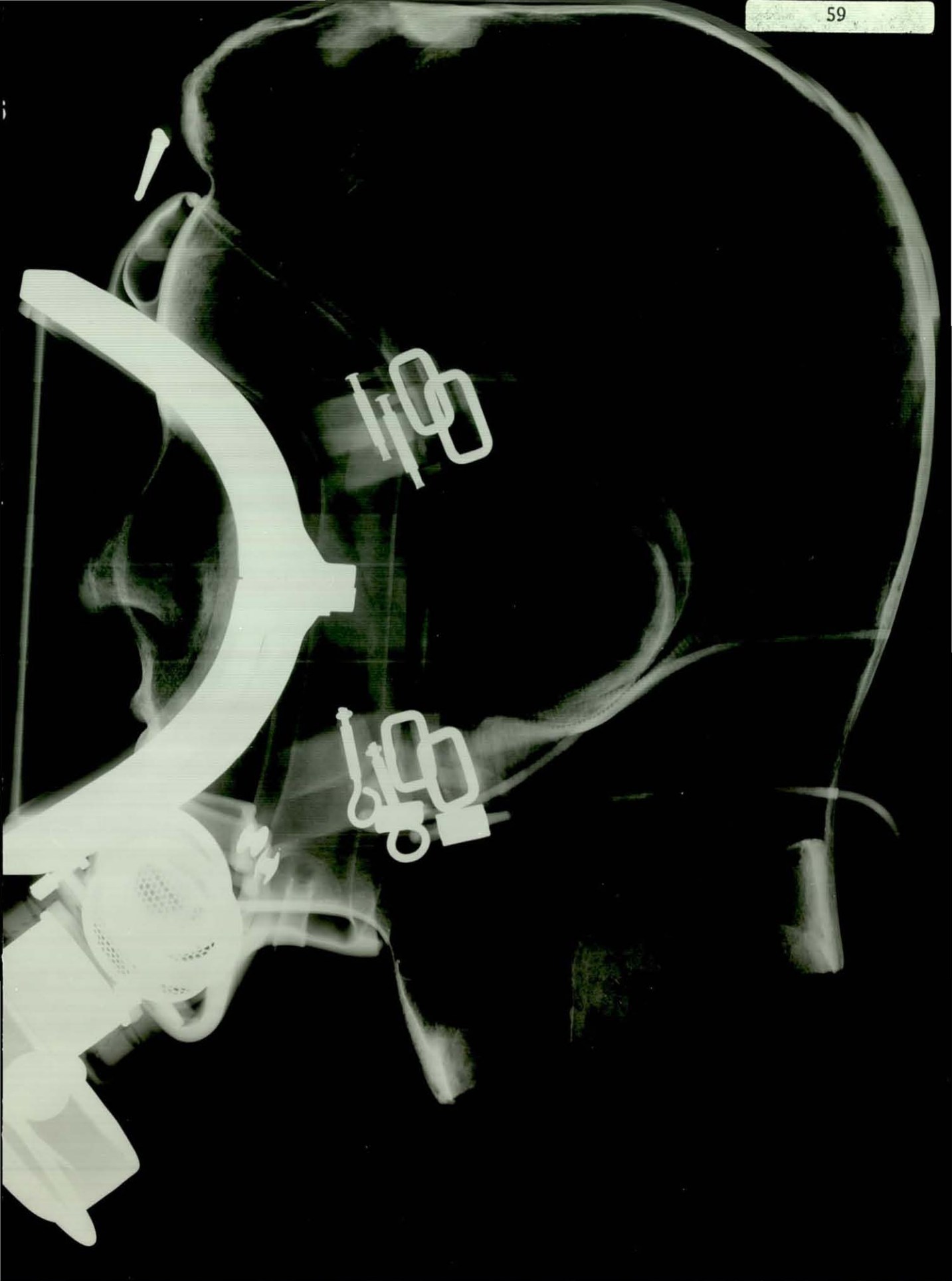


FIG No 1.7 X-Ray Cross Section

Face mask Assembly CA 2

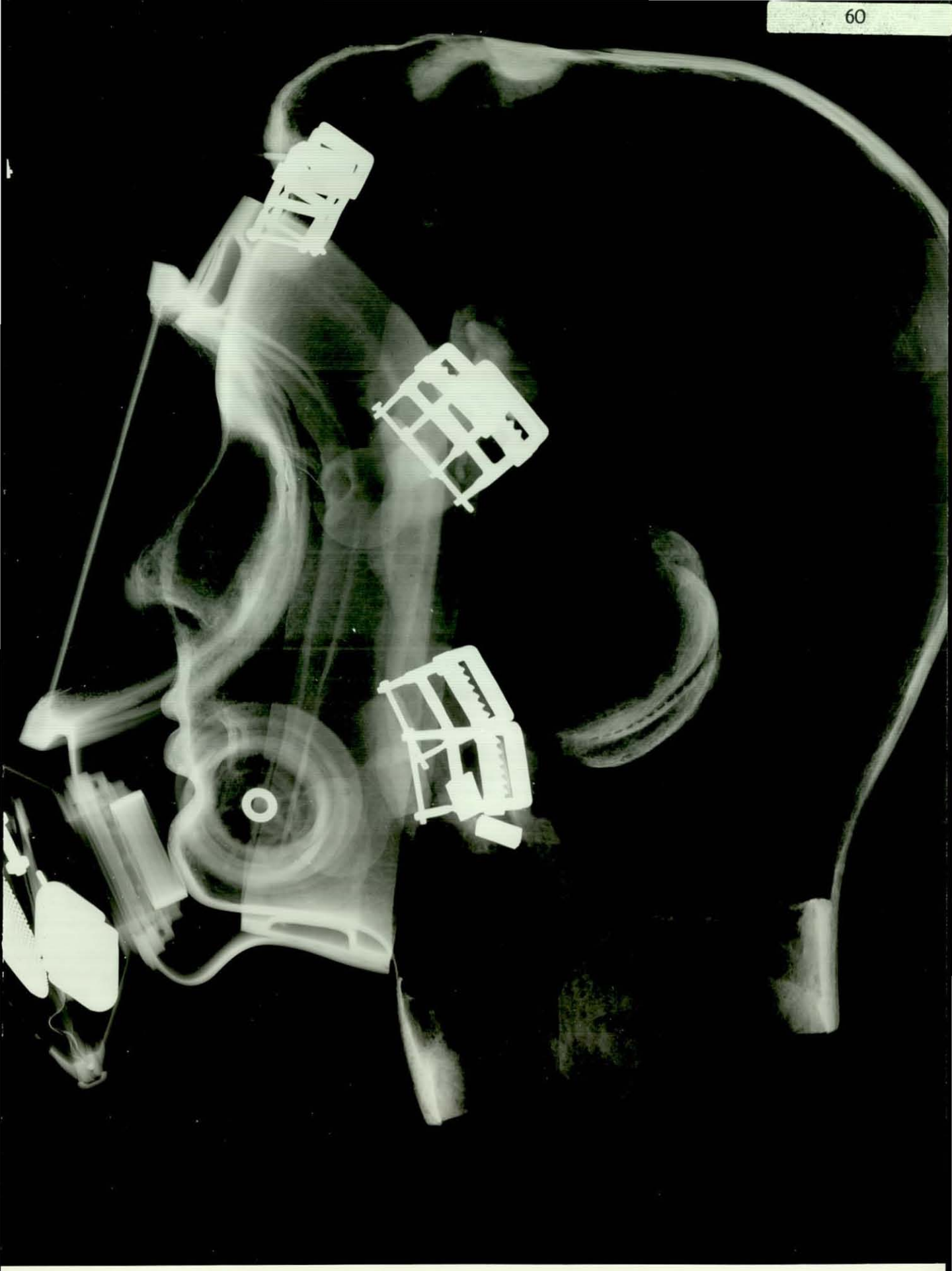


FIG No 1.8 X-Ray Cross Section

Face mask Assembly CA 3

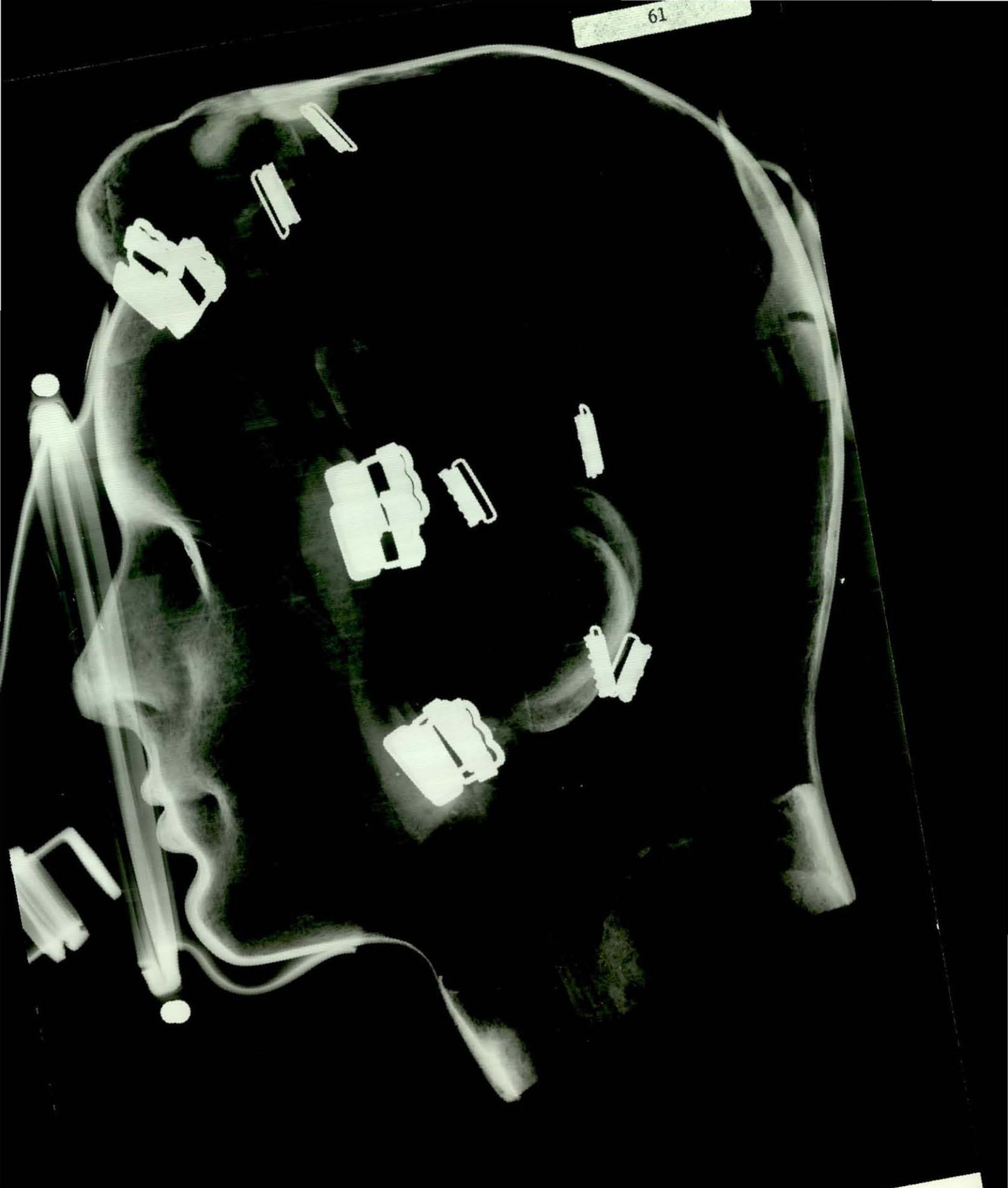


FIG No 1.9 X-Ray Cross Section

Face mask Assembly OX 1

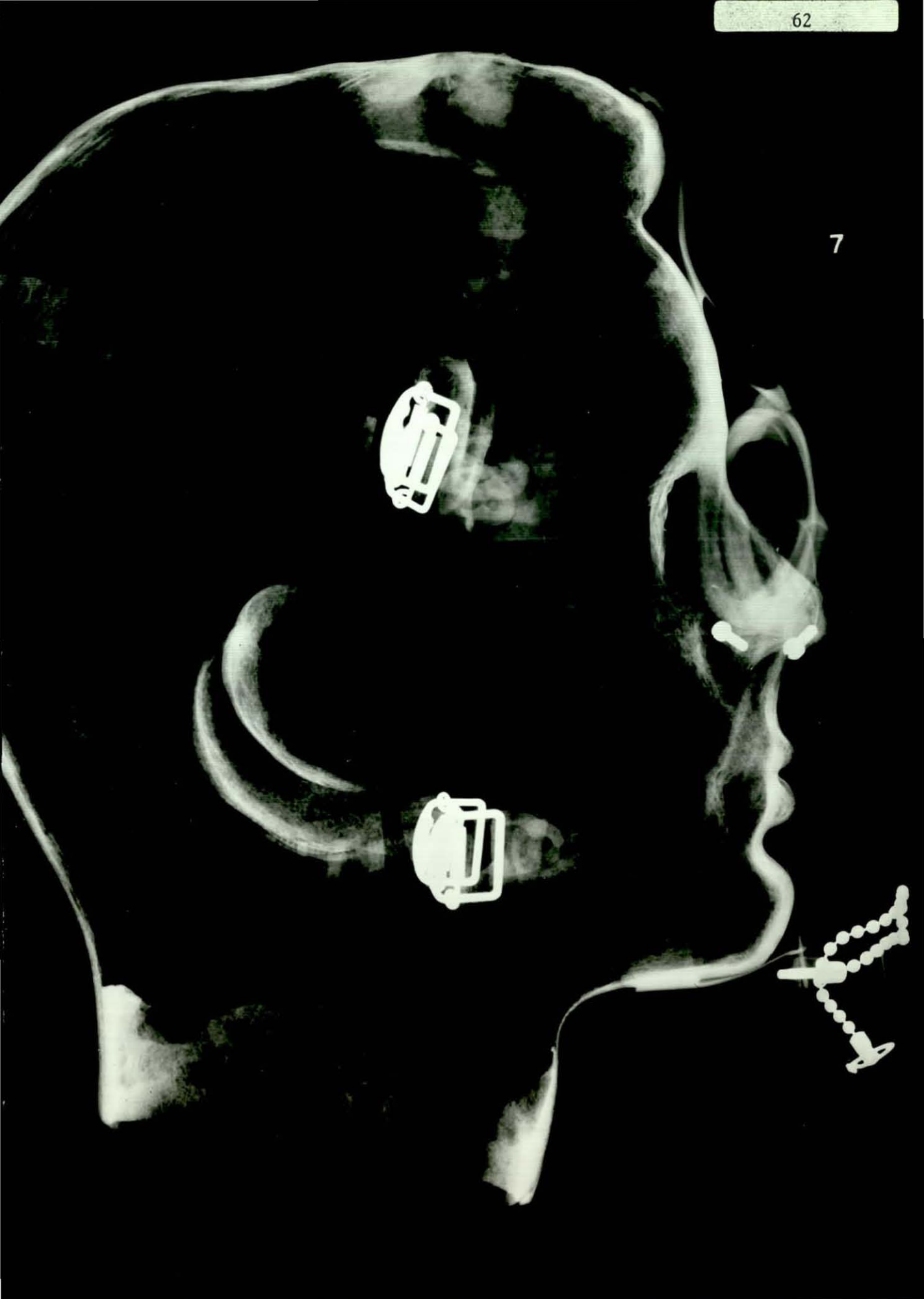
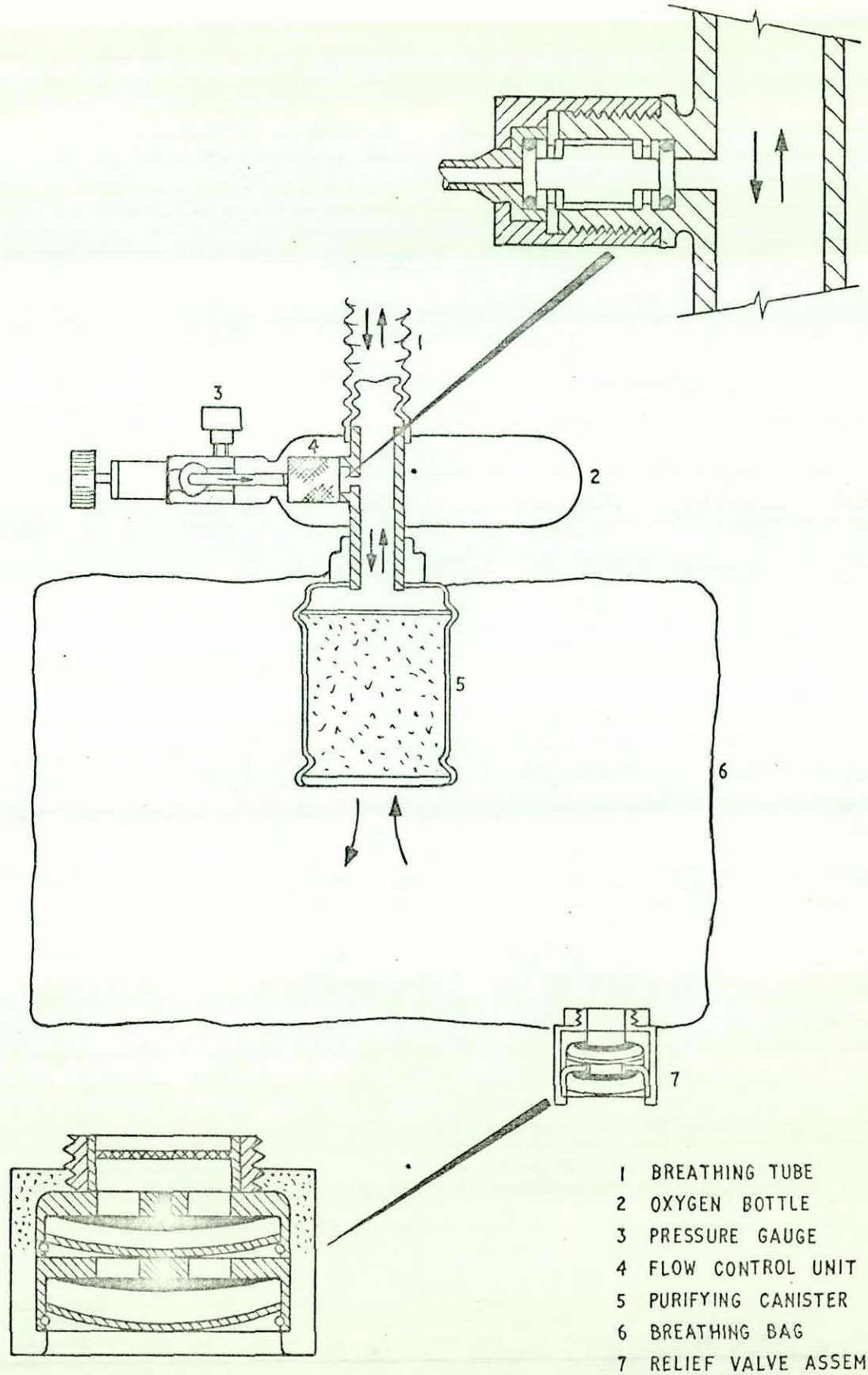


FIG No 1.10 X-Ray Cross Section

Face mask Assembly OX 2

FIG No 1.11 OX 1 Equipment - Wearing position



1 BREATHING TUBE
2 OXYGEN BOTTLE
3 PRESSURE GAUGE
4 FLOW CONTROL UNIT
5 PURIFYING CANISTER
6 BREATHING BAG
7 RELIEF VALVE ASSEMBLY

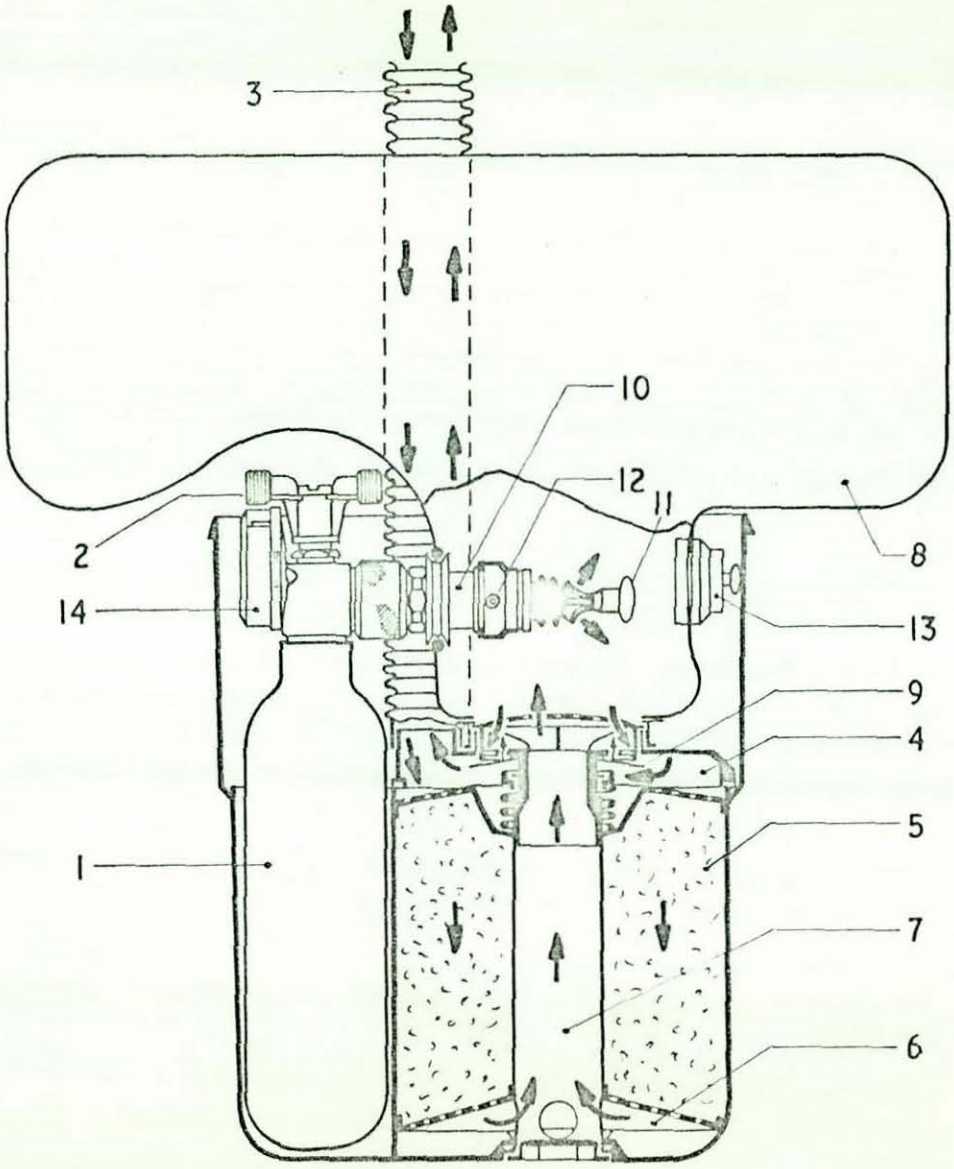
C.E.G.B S.E. REGION

DIAGRAM OF CLOSED CIRCUIT EQUIPMENT OX I. PENDULUM BREATHING

10.7.72.	A	Fig. 1.12	SER 632

FIG No 1.13 OX 2 Equipment -

Wearing position



1. OXYGEN CYLINDER.
2. CONTROL VALVE.
3. BREATHING TUBE.
4. VALVE CHAMBER.
5. SODA LIME.
6. COLLECTING CHAMBER.
7. CENTRAL PIPE.
8. BREATHING BAG.
9. NON-RETURN VALVE.
10. CONTROL VALVE.
11. CONTROL LEVER FOR LUNG DEMAND REGULATOR.
12. CONSTANT FLOW UNIT.
13. PRESSURE RELIEF VALVE.
14. PRESSURE INDICATOR.

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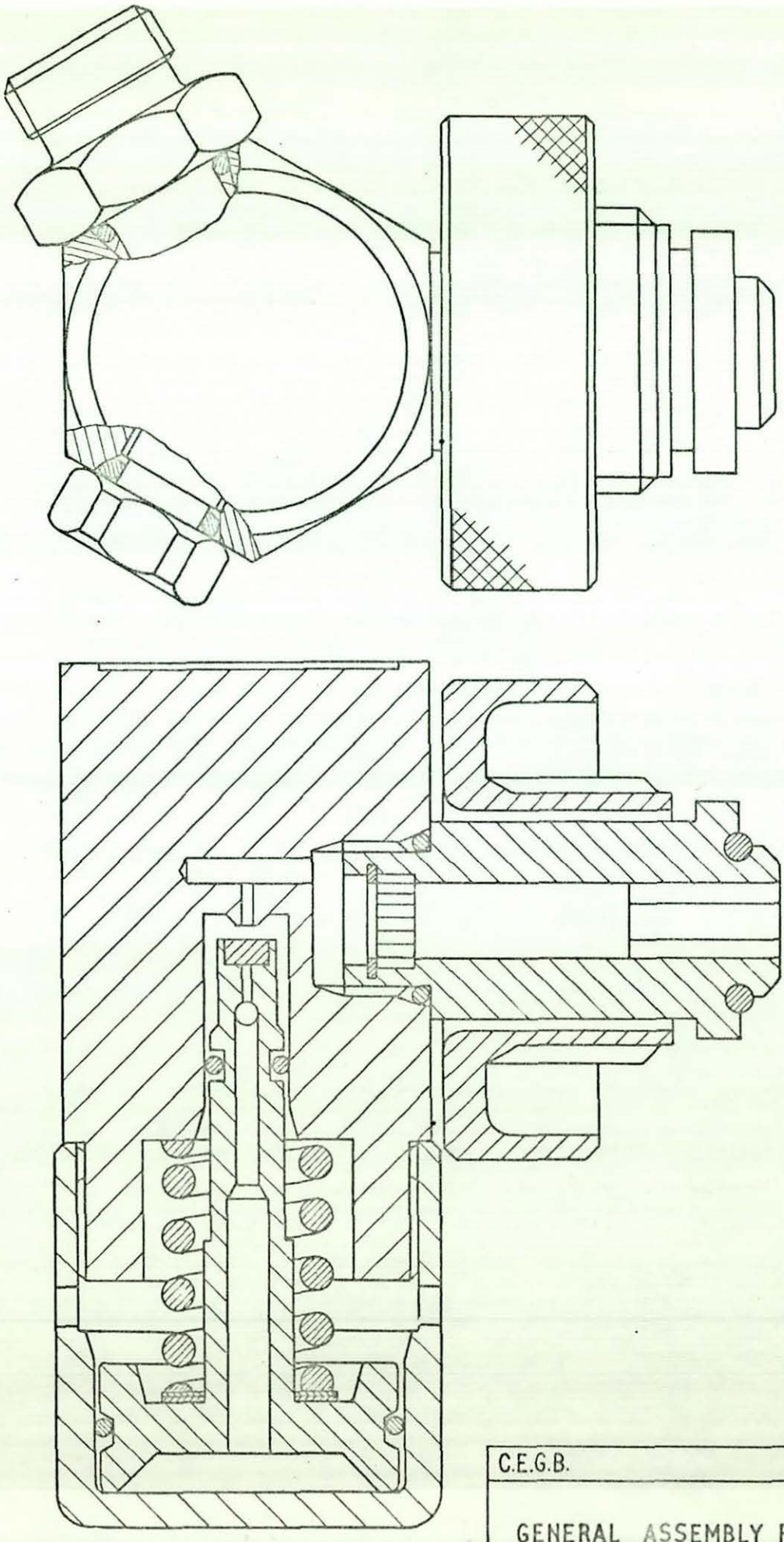
DIAGRAM OF CLOSED CIRCUIT EQUIPMENT OX 2. RECIRCULATING CYCLE.

st. ISSUE	A		Fig. 1.14	S.E.R. 632/1
2.7.72				

FIG No 1.15 CA 1 Equipment -
Wearing position with exhalation valve
connected to Kofranyi - Michaelis

FIG No 1.16 CA 2 Equipment -
Wearing position with exhalation valve
connected to Kofranyi Michaelis



C.E.G.B. S.E. REGION

GENERAL ASSEMBLY REDUCER C.A.2

st. ISSUE	A		Fig. 1.17	SER 632/4
10. 7. 72.				

FIG No 1.18 CA 3 Equipment -
Wearing position with exhalation valve
connected to Kofranyi Michaelis

CHAPTER 2

Experimental Work and Results

This chapter describes the series of bench tests, pilot physiological laboratory experiments, and field evaluations that were carried out on the short duration escape, equipments described in Chapter 1 identified as Closed Circuit Apparatus OX.1. and OX.2, Open Circuit Apparatus CA.1, CA.2, and CA.3.

2.1 Series 1 Bench Tests In the case of the closed circuit apparatus the purpose of these tests was to examine the performance of the complete assembly by physiological simulation to establish the characteristics that the design of the equipment would present to a wearer; namely resistance to breathing, composition and temperature of the gas within the closed breathing circuit relative to the effective duration of the equipment.
Evaluation of the oxygen flow component system was also undertaken to compare the various design characteristics. The tests consisted of the following.

Series 1.1. Performance tests on the fully assembled equipment to evaluate

(i) Effective duration.

(ii) Condition of breathing circuit for Oxygen and CO_2 content.

(iii) Temperature variation.

(iv) Dynamic resistance of breathing circuit at 20 and 40 respirations/min at 2 and 2½ litre tidal flow.

Series 1.2. Flow of oxygen from storage cylinders through flow control unit OX.1. apparatus and lung demand regulator OX.2.apparatus.

Series 1.3. Volumetric flow of oxygen from storage cylinders relative to time.

2.1.1 Series 1.1 Tests were made using a breathing machine to simulate the respiration cycle, this consists of two vertically mounted 6" diameter cylinders in which leather washered bronze pistons are operated in the same phase from a common crankshaft.
The crankshaft is driven by a ½HP 3 phase induction motor through a Kopp variable gear by which the simulated rate of respiration may be varied continuously during running.

Piston stroke, directly proportional to tidal volume, can be varied by altering the length of the adjustable crank.

Tidal volumes up to 4 litres can be obtained at up to 40 respirations per minute. Both cylinders are surrounded by oil baths through which oil is circulated by a pump. The temperature of the oil can be varied by electric heaters and maintained at a constant temperature if necessary.

Each cylinder is fitted with separate inlet and outlet ports and non return valves. The valves are actuated by tappets and cams according to the position of the crankshaft.

A means of injecting CO_2 into the exhale tube consists of a CO_2 cylinder, reducer, needle valve, and flow meter.

The exhale line also contains a saturation box, the temperature of which is thermostatically controlled at, or suitably above body temperature.

The gas temperatures during tests are monitored by fine thermocouples, humidities by a direct dew point method gas samples are analysed on a Pye gas chromatograph, for CO_2 and a Servomex analyser for oxygen.

Dynamic resistance at various points in the breathing cycle are measured with a mercury micro-manometer.

Temperatures, CO_2 and oxygen content are plotted continuously on a multipoint potentiometric recorder. Readings of pressure variations on the micro manometer were recorded electrically on a Devices multi channel recorder.

When testing the closed circuit breathing apparatus is positioned in a chamber approximately 2m x 1m the temperature and humidity, within the chamber was controlled to give 30°C ambient at 99% relative humidity. The mask was mounted onto a dummy head to the back of which the breathing machine was connected. Figure 2.1 Page 112 shows the circuit of the breathing machine with an equipment under test.

2.1.2 Procedure and results. Series 1.1 Tests The oxygen equipments were assembled in accordance with the manufacturers instructions. Cylinders were charged under controlled conditions to the prescribed pressure (200 bars) and the CO_2 purifier was weighed and the containers charged. These were then placed on a horizontal reciprocating tray and agitated at 190 cycles per minute for 3 minutes to compact granules. A leak test at negative pressure was then carried out and the resistance to breathing of the circuit was measured. The equipments were then placed in the chamber, the facemasks were mounted on the dummy head and the breathing machine was set in operation at 20 ventilations per minute at 2 litre tidal flow. After 10 minutes this was increased to 40 respirations per minute the tidal flow remaining constant. Tidal flow was then increased to 2½ litres and a further set of readings taken. A 5% CO_2 concentration was injected into the exhale tube of the breathing machine circuit after 30 seconds. Each equipment was tested 5 times and the averaged results of these tests are shown in Table 2.1.

Performance	Unit	OX.1	OX.2
Resistance static	mmH_2O	21.3	17 in 25 ex
Resistance at 40l flow *	"	25.3	17 " 30 "
Resistance at 80l flow *	"	104.14	52 " 75 "
Resistance at 100l flow *	"	134.78	Not recorded. *
O Content Start	%	98	78
O " Finish	%	23.2	22.8
CO_2 " Start	%	0.1	0.4
CO_2 " Finish	%	2.1	2.0
Temperature Start	^oC	23	23
" Finish	^oC	42	39.42
Effective duration minute		19.6	36.35

*4.2 litre breathing bag collapsed at this breathing rate

TABLE 2.1. Averages of five simultation tests OX.1 and OX.2 Equipment

2.1.3 Series 1.2 Tests were undertaken to establish on a comparative basis the performance of the capillary flow control unit OX.1 and the constant flow lung demand assembly (OX.2).

2.1.4 Procedure and Results The oxygen storage cylinders were charged under controlled conditions to the prescribed pressure (200 bar) and the outlet side of the assembly was coupled to an oxygen 'rotameter' gauge. The cylinder valve was opened and reading of flow were recorded as shown in Table 2.2 and Figure 2.2. Pg.113.

* Resistance has been expressed as the pressure drop through the breathing circuit.

TIME Minutes	OX.1. Cylinder				OX.2. Cylinder			
	1	2	3	Av	1	2	3	Av
0	8.9	9	8.8	8.9	1.5	1.5	1.5	1.5
.25	8.5	8.7	8.4	8.5	1.5	1.5	1.5	1.5
.5	7.8	8.1	8	7.9	1.5	1.5	1.5	1.5
.75	7.3	7.6	7.7	7.6	1.5	1.5	1.5	1.5
1-0	6.9	7.4	7.4	7.3	1.5	1.5	1.5	1.5
1-5	6.4	6.7	6.6	6.5	1.5	1.5	1.5	1.5
2	6	6	6	6	1.5	1.5	1.5	1.5
3	5	5	5	5	1.5	1.5	1.5	1.5
4	4.4	4.2	4.2	4.3	1.5	1.5	1.5	1.5
5	3.6	3.5	3.4	3.5	1.5	1.5	1.5	1.5
6	3.1	2.9	2.9	2.9	1.5	1.5	1.5	1.5
7	2.6	2.4	2.4	2.4	1.5	1.5	1.5	1.5
8	2.2	2	1.9	2.0	1.5	1.5	1.5	1.5
9	1.8	1.7	1.7	1.7	1.5	1.5	1.25	1.45
10	1.5	1.4	1.4	1.4	1.5	1.5	1.5	1.5
11	1.3	1.2	1.2	1.2	1.5	1.5	1.25	1.45
12	1.1	1.0	1.0	1.0	1.5	1.25	1.5	1.45
14	.7	.7	.6	.66	1.2	1.5	1.5	1.4
16	.4	.4	.4	.4	1.5	1.5	1.5	1.5
18	-	-	-	-	1.5	1.5	1.5	1.5
20	-	-	-	-	0.5	0.6	0.5	0.5

TABLE 2.2 - Flow from Oxygen storage cylinders

Litres/min. using Rotameter

2.1.5 Series 1.3 Tests were undertaken to establish on a comparative basis the volumetric flow of oxygen from storage cylinders through capillary flow control unit (OX.1) and constant flow lung demand assembly (OX.2).

2.1.6 Procedure and Results The oxygen storage cylinders were charged under controlled conditions to the prescribed pressure (200 atms) and the outlet side of the assembly was coupled to a laboratory gas meter of the wet type. The cylinder valve was opened and readings of volumetric flow were recorded as shown in Table 2.3 and Fig.2.3. Page 113.

TIME MINS	OX.1 CYLINDER	OX.2 CYLINDER
0	0	0
2	13.05	2.77
4	23.0	5.21
6	29.5	7.59
8	34	9.94
9	36	11.09
10	37.3	12.20
12	39.5	14.53
14	41.25	16.82
16	41.8	19.06
18	42.75	21.32
20	43	23.58
26	43.75	30.55
30	-	35.17
35	-	41.05
39.5	-	45.61

OX.1 1st CYLINDER - 43.75 litres
OX.1 2nd CYLINDER - 43.25 "
OX.1 3rd CYLINDER - 43.75 "

OX.2 1st CYLINDER 45.61 litres
OX.2 2nd CYLINDER 45.73 "
OX.2 3rd CYLINDER 45.63 "

TABLE 2.3 Total Volumetric Flow from Oxygen storage cylinder in Litres using wet type gas meter

2.2. Series 2 Bench Tests In the case of the open circuit apparatus the purpose of these tests were to determine the characteristics of performance of the inspiratory and expiratory valve assemblies fitted to open circuit apparatus CA1, CA2 and CA3. The inhalation valve assemblies were of the demand type and a brief description of their design is given in Chapter 1. The exhalation valve assemblies were of the simple non-return type consisting of a rubber mushroom with associated seating mounted in an adaptor which clamped into the full face mask of the respective apparatus.

The important factors in the performance of these valve assemblies is listed below in the considered order of their physiological consequence.

(i) Resistance to air flow.

(ii) Leakage dynamic and static.

(iii) Opening pressure.

(iv) Location of valves - orientation in the breathing circuit.

(v) Protective mechanisms - against damage and atmospheric conditions.

In this research work only resistance to air flow has been investigated.

Resistance to air flow of valves for respiratory protective equipment depends upon the flow conditions used to determine the resistance. The nature of flow in the inspiratory valve assembly will depend upon the nature of the approach of the air flow to the valve. In the case of open circuit equipment CA.1 and CA.3 this was initially at a variable high pressure (200 bar) and in the case of CA.2 equipment at a constant pressure of (7.5 bar).

The flow conditions for the exhalation valve assembly are complicated by several factors. Expired air is nearly saturated by several factors and is in a turbulent condition. This

turbulence is ascribable to the anatomy of the respiratory passages. These passages are made up of several connecting branches that join into one main tube the trachea which conducts the air through a curved path to the outside. None of these paths are rigid or straight and the movement and change in cross section may induce some turbulence. Cooper(1961) and Silverman et al (1943)have reported fully on investigations into fundamental factors and for the purpose of these investigations the valve performance has been evaluated on the law of air flow through orifices or openings for a range of flow rates from 20 to 200 litres/min.

2.2.1 Procedure and Results Series 2.1. In these tests the purpose was to evaluate the resistance of the demand valve assemblies under a constant flow condition. Fig.2.4 Pg.114 shows a schematic layout of the method. Observations are made of the resistance and recorded in mm H_2O from 10 litres to 200 litres constant flow. Each assembly was tested 5 times and the averaged results of these tests are shown in Table 2.4 the observed results being similar for each test.

Supply Pressure bar		Flow in Litres	Resistant mm H_2O		
CA.1 & CA.3	CA.2		CA.1	CA.2	CA.3
210	6.4	0	22,86	30.48	22.1
"	6.7	20	50.8	25.4	57.15
"	6.5	40	55.08	25.4	58.42
"	6.6	80	68.58	20.32	62.23
"	6.7.	100	72.39	17.78	76.04
"	6.7	150	77.63	15.24	73.66
"	6.7	200	101.6	15.24	86.36

TABLE 2.4 Averaged results of 5 tests of resistance demand valve assemblies CA.1, CA.2, CA.3 under constant flow flow conditions.

The results indicate that the use of a 1st stage reducer in the breathing circuit offers an advantage to the inhalation resistance.

2.2.2 Procedure and Results. Series 2.2. In these tests the purpose was to evaluate the resistance of the exhalation valve assemblies under a constant flow condition Fig 2.5 shows a schematic layout of the method. Observations were made of the resistance and recorded in mm H_2O from 10 to 200 litre constant flow. Each assembly was tested 5 times and the averaged results of these tests is shown in Table 2.5

Flow l/min	Resistance in mm H_2O		
	CA.1	CA.2	CA.3
0	0	0	0
20	7.62	7.62	12.7
40	12.7	12.7	12.7
80	17.78	15.24	19.05
100	22.86	20.32	25.4
140	30.48	27.94	38.1
160	40.64	31.02	41.94
180	43.18	35.56	43.45
200	43.18	38.1	40.64

TABLE 2.5 Averaged results of 5 tests of resistance exhalation valve assemblies CA.1, CA.2, CA.3 under constant flow conditions.

These tests indicated no significant variation in the performance of these exhalation valves the design characteristics being very similar ie an orifice for passage of air and a rubber mushroom flap for closure or opening of the orifice. See Figs 1.2, 1.3 and 1.4. pages 54, 55 and 56.

2.3 Pilot physiological investigations Following the series of bench tests previously described, a number of pilot experiments were conducted in a laboratory to establish a basis of performance for comparison with the simulated bench tests and behaviour of apparatus when worn by experienced subjects and to evaluate and prove a series of proposed methods of test for future physiological assessment of inexperienced wearers of respiratory protective devices.

The three subjects participating in the pilot physiological experiments 2 male and 1 female were all trained in experimental physiological investigations and skilled with ventilating facemask apparatus. Their physical characteristics are designated in Table 2.6 below.

CODE			JD	AH	AW
Sex			M	FM	M
Age years			41	25	21
Weight	kg		76.23	58.03	59.91
Height	m		1.788	1.6	1.651
Chest Circumference	cm.	*	93,3	85.7	82.3
depth	mm	*	226	174	275
width	mm	*	274.5	234	168
Vital Capacity	l	**	4,8	4.25	4.6

TABLE 2.6 Subject Data Laboratory Experiments.

*Chest measurements were taken with a Harper anthropometer and steel tape as follows:-

Circumference - at nipple line on expansion, arms relaxed at side

Depth - at mid manubrium to the spinous process of dorsal vertebra.

Width - at mid axillary plane with probes in contact with ribs.

** Vital Capacity was taken from the nomograph prepared by Miller et al (1959).

2.4 Series 3 - Laboratory Tests were associated with the wearer evaluation of the open circuit equipments CA.1, CA.2 and CA.3 and closed circuit equipments OX.1 and OX.2 In the experiments the relationship under an imposed respiratory resistance between work load(using a cycle ergometer)oxygen uptake and respiratory work rate were studied.

2.4.1 Equipment used Muller cycle ergometer with facility for continuously increasing work rate, coupled with pacemaker.

*Kofrany Michaelis - respirometer for measurement of the expired air volume and air temperature.

*Beckman D.2S. paramagnetic oxygen analyser for determination of Oxygen partial pressure and calibrated to read % by volume.

Scalamp - thermocouple galvanometer for temperature measurements

Servomex - analyser 0.150 ml/min for oxygen measurement

Cambridge quick response gas analyser for CO_2 measurement

*Open circuit apparatus evaluation only.

Schematic diagrams of the equipment are shown in Fig.2.6 and Fig.2.8 Pages 116 and 118. The cycle ergometer was equipped with a whirling current braking system ie the wheel had a copper tyre turning between the poles of two strong permanent magnets. The work load being determined by the position of the magnets which were adjustable by dipping the copper tyre more or less deeply into the magnet gap. The power of the electric whirling current generated by the turning of the wheel having a braking effect, determined by the position of these magnets. Pedalling speeds could be varied to 40,60 and 90 revolutions/min. The height of saddle was also adjustable to suit the height of subjects under test. Prior to the commencenent of this series of investigation a calibration test was carried out on the ergometer.

The Kofrany Michaelis meter is a dry gas meter for measuring the total volume of expired air during an activity and has a facility to sample at 0.3 or 0.6% the exhaled gas into a 100ml butyl rubber bag.

It is 20cm wide x 27cm high and 11cm deep and weighs approximately 3Kg, and can be worn by a subject strapped to the back or the front of the chest or be conveniently set at the side of the subject on a table or chair.

The work load of wearing the meter is considered insignificant and experiments to this effect were reported by Consolazio et al(1963).

A diagram of the mechanism is shown in Fig 2.7. Page 117 and a brief description of its operation is as follows.

The meter consists of two chambers. Each chamber is divided into two half chambers by a moveable partition of leather so that when one chamber is filled the other is emptied. These partitions transfer their movements over a lever system to a crankshaft(2) which turns a counting mechanism and controls the sliding valves in such a way to allow the half chambers to fill and empty alternatively.

The sliding valves are pressed on the valve lids by metal springs(5) and (6) to remain closed in any position of the meter.

The expired air enters by the entry port(1). The mechanism for extraction of the sample consists of a double membrane pump(13). The rubber membranes are tightened to the pump bars (12) and (14). These again are connected to each other by a metal ring which is moved by the excentric (4) on the crankshaft (2). The connecting tubes (15) to (19) between membrane pump and air valve are copper tubing and small rubber tubes.

The direction of air flow from the membrane pump to the rubber sample bladder coupling (3) is regulated by a 3 way tap (11). In the left hand level position of the tap (11) the route to the exit port (3) is closed. In the right hand level position of the tap both valves of the double membrane pump fill the rubber bladder at a 0.6% take off. In the vertical position 0.3% sample

take off is made.

The movement from horizontal to vertical of level assembly (10) meshes gear wheel (23) to gear wheel (24) and continuous registration of the expired air is made.

2.4.2 Procedure & Results. Series 3.1 laboratory investigation was associated with the evaluation of open circuit compressed air apparatus CA.1, CA.2 and CA.3. Prior to each test the cylinders were charged under controlled conditions the inhalation and exhalation resistance of the assembled equipment was measured and recorded. The cycle ergometer saddle was adjusted to appropriate setting for the subjects height and set to a constant work rate loading of 50 watts at 60rpm. The subject wearing the apparatus then pedalled the ergometer until the cylinder contents were exhausted. Measurements were taken at one minute intervals of volume of air expired. Temperature of air in the face mask in the vicinity of the breathing zone and % oxygen and CO_2 content in the expired air.

As previously stated a team of three people participated in these tests, three tests being undertaken on the same day each subject wearing a different equipment. The test cycle was repeated at weekly intervals (so that fatigue would not enter into consideration of the apparatus) until each subject had worn each set once. The results of these tests are shown in Tables 2.7, 2.8, and 2.9. From these tests it was established that the Average Minute Volume for the three subjects was 21.0 for CA.1, 26.4 for CA.2 and 26.2 for CA.3. CO_2 concentration for CA.1 was higher, which could be attributed to the position of the demand valve giving a lower pressure in the face mask on inhalation, therefore, poor clearance of dead space in the mask.

Subjective evaluation of the equipment by the wearers was unanimous in rating the equipments in order of preference as CA.1, CA.2 and CA.3. The flexible visor of the face mask of CA.1 apparatus did however cause annoyance by contact with the nose of all subjects see Fig 1.5 page 57 and this was modified to a more rigid visor as shown in Fig 1.6 page 58 no other modifications were made at this stage of the investigations.

			TIME IN MINUTES																
Subject		INS. AIR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
J.D.	%O	21.0		17.6		16.6		16.5		16.5		16.5		16.5		16.2		16.3		16.3
(7.3.70).	L/MIN	0	12	17	20	21	18	22	24	23	25	27	24	23	26	25	30	27	25	14
	T^0C	25	25	25	25	25	25	25	25	26	26	26	26	26	26	26	26	26	26	26
A.H.	%O	21.0		17		17		17		16.5		16.5		16.5		16.5		16.5		
(21.3.70)	L/MIN	0	11	11	15	17	17	20	23	22	20	20	21	19	21	18	19	19	19	
	T^0C	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	26	26	26	
A.W.	%O	21.0		16.5			16		16		16		16.5		16.5		16.5		16.5	
(7.3.70)	L/MIN	0	12	13	15	18	18	22	20	23	22	20	21	23	22	28	21	24	24	16
	T^0C	25	25	25	25	25	25	25	25	25	25	26	26	26	26	26	26	26	26	26

SUMMARY

Subject		J.D.	A.H.	A.W.
Date		7. 3.70.	21. 3.70.	7. 3.70.
Total Volume Exhaled	(l)	414	312	362
Time	(min)	17.5	16.4	17.6
Minute Volume Exhaled(Min)	(l)	12	11	12
Minute Volume Exhaled(max)	(l)	30	23	28
Average Minute Volume Exhaled	(l)	23.65	18.99	20.49
Maximum CO_2 Exhaled	%	4.8	4.5	5
Maximum Exhalation Temperature	^0C	26	26	26

20 litre flow

Inhalation resistance 35 mm H_2O
Exhalation resistance 10 mm H_2O

Average Minute Volume Exhaled for 3 Subjects
21.04 litres

TABLE 2.7. Observed Results.Pilot Investigations
50 watt Constant Work Rate on ergometer
Open Circuit Compressor Air Apparatus CA.1

			TIME IN MINUTES															
Subject		INS. AIR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
J.D.	%0	20.25		17.5		16.8		17.0		16.8		16.8		16.8		16.8		17.0
(8.4.70).	L/MIN	0	22	24	25	25	18	23	33	28	33	27	29	30	30	30	30	6
	T^0C	25	25	25	25	25	25	25	25	25	26	26	26	26	26	26	26	26
A.H.	%0	21.0		18		17.5		17		16.5		16.5		16.2				
(21.3.70)	L/MIN	0	19	24	20	30	29	30	31	26	30	28	28	31	9			
	T^0C	25	25	25	25	25	25	25	25	25	25	25	25	25	25			
A.W.	%0	21.0		18.1		17.3		17		17.2		17.2		16.8		16.5		
(7.3.70)	L/MIN	0	18	24	29	30	31	29	33	30	31	31	28	29	28	29	19	
	T^0C	25	25	25	25	25	25	25	25	25	26	26	26	26	26	26	26	

SUMMARY

Subject		J.D.	A.H.	A.W.
Date		8. 4.70.	21. 3.70.	7. 3.70.
Total Volume Exhaled	(1)	413	329	420
Time	(min)	16.2	12.3	15.6
Minute Volume Exhaled (Min)	(1)	22	19	19
Minute Volume Exhaled (Max)	(1)	33	31	33
Average Minute Volume Exhaled	(1)	25.49	26.67	26.91
Maximum CO_2 Exhaled	%	3.45	4.8	4.5
Maximum Exhalation Temperature	^0C	26	25	26

20 litre flow

Inhalation resistance 12 mm H_2O
Exhalation resistance 8 mm H_2O

Average Minute Volume Exhaled for 3 Subjects

26.36 litres

TABLE 2.8. Observed Results.Pilot Investigation

50 watt Constant Work Rate on ergometer

Open Circuit Compressor Air Apparatus CA.2

Subject		INS. AIR	TIME IN MINUTES 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
J.D.	%O	21.0		16.0		16.0		16.3		16.1		16.8		17		17		16.8
(21.3.70)	L/MIN	0	16	18	22	25	27	26	26	28	28	30	29	31	30	33	37	6
	$T^{o}C$	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
A.H.	%O	20		17		16.5		16.5		16.8		17		17		17		
(8.4.70).	L/MIN	0	18	25	23	24	22	24	26	28	26	26	28	26	28	26	19	
	$T^{o}C$	26	26	26	26	26	26	27	27	27	27	27	27	27	27	27	27	
A.W.	%O	19.5		16.7		16.3		16.5		16.7		16.6		17		17.2		16.5
(7.4.70)	L/MIN	0	11	22	21	25	23	25	25	25	22	25	27	30	33	34	34	28
	$T^{o}C$	26	26	26	26	26	25	25	25	26	26	26	26	26	26	26	26	26

SUMMARY

Subject		J.D.	A.H.	A.W.
Date		21.3.70.	8. 4.70.	7. 4.70.
Total Volume Exhaled	(l)	412	369	410
Time	(min)	15.33	14.6	15.4
Minute Volume Exhaled (Min)	(l)	16	18	11
Minute Volume Exhaled (Max)	(l)	37	28	34
Average Minute Volume Exhaled	(l)	26.86	25.15	26.54
Maximum CO_2 Exhaled	%	4	3.5	3.2
Maximum Exhalation Temperature	^{o}C	25	27	26

20 litre flow

Inhalation resistance 42 mm H_2O
Exhalation resistance 6.35 mm H_2O

Average Minute Volume Exhaled for 3 Subjects

26.19 litres

TABLE 2.9. Observed Results.Pilot Investigation

50 watt Constant Work Rate on ergometer

Open Circuit Compressor Air Apparatus CA.3

2.4.3 Procedure and Results Series 3.2 laboratory investigation was associated with the evaluation of closed circuit oxygen apparatus OX.1 and OX.2. The method was similar in nature to that used for Series 3.1 with the exception of the observations made. As the breathing circuit was a closed system the following readings were taken in the breathing zone of the face mask at 1 minute intervals during the test, % oxygen % CO_2 and temperature of the gas mixture.

A subject under test is shown in Fig 2.9, Page 119 and observed results are shown in Table 2.10 and 2.11.

From these tests it was established that the equipments functioned satisfactorily as a closed circuit system. For OX.1 the average duration of the set was 17 minutes and the oxygen content at minimum level on completion of the longest duration was 20.8%. The carbon dioxide content reached a maximum of 2.8% this being considered acceptable for emergency escape purposes it would however be preferable for this not to exceed 1%. All subjects felt that the breathing resistance increased as the tests progressed. The objectionable feature being the high temperature 44^{o}C at the end of experiment.

For OX.2 the tests were terminated after 15 minutes duration all subjects found the close fitting face mask intolerable and the temperature of the gas mixture appeared subjectively higher than the OX.1 equipment. The CO_2 concentration ranged from 0.25% to 2.2 during the test duration which could be attributed to the constant flow of oxygen of 1.5 l/min compared with the initial flow of the OX.1 equipment of 7 litres.

Following these tests it was decided to withdraw the OX.2 equipment from further evaluations.

Subject		INS. AIR	TIME IN MINUTES 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
J.D. (20.2.70).	%O	21	70	80	73	54	52	46	39	32	32	29	26	25	27	23	22	22	21	
	$\%CO_2$	0	0	0	0	0	0	0	0	0	0.1	0.2	0.6	0.9	1.0	1.3	1.8	2.3	2.2	
	Temp ^0C	2.4	25	28	29	30	32	37	34	36	38	39	40	41	42	43	44	44	44	
A.H. (16.1.70).	%O	21	93	89.1	79.7	49	49	40	30.6	32.9	29	31	31	31	26.9	25.4	24.2	23.4	21	20.8
	$\%CO_2$	1.0	0	0	0	0	0	0	0	0	0.1	0.3	0.4	0.2	0.3	1.0	2.1	2.6	2.8	2.7
	Temp ^0C	24	25	28	30	32	34	35	36	36	38	39	40	41	41	42	42	42	42	43
A.W. (20.2.70).	%O	21	*57	48	46.5	43	38	30	29	24	28	26	23	23	22	23	22	21.2		
	$\%CO_2$	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0.6	1.0	1.8	2.2		
	Temp ^0C	24	27	29	31	33	34	36	37	38	39	41	41	42	43	43	43	44		

SUMMARY

Subject	J.D.	A.H.	A.W.
Date	20. 2.70.	16. 1.70.	20. 2.70.
Respiratory resistance mm H_2O	25	25	25
Work rate watts	50	50	50
Volume 0 l	42	42	42
Duration of sets mins	17	18	16
O_2 concentration min %	21.0	20.8	21.2
O_2 concentration max %	80	93	57
Gas temperature min ^0C	24	24	24
" " max ^0C	44	43	44
Temperature rise ^0C	20	19	20
CO_2 max %	2.3	2.8	2.2

TABLE 2.10

Observed Results. Pilot investigation

50 watt Constant Work Rate on ergometer

Closed Circuit Apparatus OX.1

* Low oxygen content due to sluggish valve

Subject		INS. AIR	TIME IN MINUTES 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
J.D. (16.1.70).	%O	21	59.5	59	62	58.5	55.7	53	54.5	49.2	49	46.5	40	38	35.3	32.5	29.0
	$\%CO_2$	0	0.3	0.6	0.8	1.1	1.2	1.3	1.3	1.6	1.8	1.8	1.9	2.0	2.0	2.0	2.1
	Temp ^0C	24	25	25	26	30	32	32	34	34	36	37	37	38	38	39	40
A.H. (20.1.70).	%O	21	51.2	61.9	60.0	61.1	57.1	51.4	48.4	44.2	45.5	41.5	32.6	26.9	25.5	23.4	21.9
	$\%CO_2$	0	0.3	0.5	0.6	0.9	0.9	1.3	1.3	1.3	1.6	1.8	1.8	1.9	2.1	2.1	2.1
	Temp ^0C	24	25	26	28	31	32	34	35	35	37	38	39	40	40	41	41
A.W.	%O	21	69	73	64.5	61.4	59.8	57	52	45	44.8	41.0	37.5	33	30	28	24.3
	$\%CO_2$		0.2	0.3	0.5	0.8	1.3	1.3	1.3	1.4	1.5	1.5	1.6	1.8	1.9	2.1	2.2
	Temp ^0C	24	25	26	29	31	32	34	35	34	35	37	37	38	39	39	39

TESTS WERE TERMINATED AFTER 15 MINUTES

SUMMARY

Subject	J.D.	A.H.	A.W.
Date	16. 1.70.	20. 1.70.	5.12. 69.
Respiratory resistance mm H_2O in	17	17	17
ex	25	25	25
Work rate watts	50	50	50
Volume 0 l	42	42	42
Duration of sets mins	15	15	15
O_2 concentration min %	29.0	21.9	24.3
O_2 concentration max %	62	61.9	73
Gas temperature min ^0C	24	24	24
" " max ^0C	40	41	39
Temperature rise ^0C	16	17	16
CO_2 max %	2.1	2.2	2.2

TABLE 2.11

Observed Results. Pilot investigations

50 watt Constant Work Rate on ergometer

Closed Circuit Apparatus OX.2

2.5 Series 4 field investigation was associated with the evaluation of compressed air equipments CA.1, CA.2 and CA.3 to show the suitability of these sets under an emergency escape condition when worn by experienced wearers.

2.5.1 Procedure and Results Series 4 The tests consisted of a descent from the 7th floor of a nuclear reactor building down the staircase to the ground floor (180 ft vertical height) and ascent back to the 7th floor via the passenger lift wearing the apparatus and a Kofrani Michaelis meter worn haversack fashion, coupled to the exhalation valve of the face mask. Fig.1.15 page 67. Measurements of the volume of air exhaled by the wearer during the exercise was made together with the $\%CO_2$ in the exhaled air.

A team of three people took part on this work subject data is shown in Table 2.12 below. Three test runs were undertaken so that each person used each set once. The tests were run on three consecutive days so that fatigue would not enter into consideration of the apparatus. After each test the number of cycles of the course was recorded together with the subjective opinions of the wearers. These results are shown in Table 2.13.

Code		MR	HK	JD*
Sex		M	M	M
Age years		38	33	40
Weight	kg	73.05	70.72	74.41
Height	m	1.75	1.72	1.64
Chest	cm	94.6	99.1	92.7
Vital Capacity	l	4.81	4.76	4.17

* Moderate smoker

TABLE 2.12 Subject Data Field experiments.

Subject Code	Observations	CA.1	CA.2	CA.3
	Date	26.4.70.	24.4.70.	25.4.70.
MR	Distance Completed *	1000	860	1075
	Time min.	9.75	10.25	10.5
	Volume Exhaled l	340	358	370
	CO_2 %	4.8	4.6	4
	AV Minute Volume l	34.87	23.92	35.2
	Date	25.4.70.	26.4.70.	26.4.70.
HK	Distance Completed *	645	645	545
	Time min.	7	7	7
	Volume Exhaled l	341	354	343
	CO_2 %	5	4.8	3.5
	AV Minute Volume l	48.7	50.57	49.0
	Date	24.4.70.	25.4.70.	26.4.70.
JD	Distance Completed *	721	695	860
	Time min.	9.5	7.5	8.75
	Volume Exhaled l	348	300	360
	CO_2 %	4.5	4.5	3.4
	AV Minute Volume l	36.6	40.28	41.1

TABLE 2.13 OBSERVED RESULTS EXPERIENCED WEARERS
CA.1, CA.2 & CA.3 Equipments

*The distance completed is shown in the number of steps covered by the subject, in the descent from 7th level to ground there were 215 steps made up as follows :-

7th to 6th level	23	TOTAL
6th to 5th level	27	50
5th to 4th level	26	76
4th to 3rd level	39	115
3rd to 2nd level	25	140
2nd to Mezanine	49	189
Mezanine to Ground	26	215

When the equipment was exhausted at 3rd descent 3rd floor total number of steps was recorded as 760.

The following is a summary of the comments about each set made by the wearer

CA.1 Apparatus

This was the unanimous choice of all three wearers. The mask was found to fit well and the breathing hose operating at atmosphere pressure was found to be very flexible. As an emergency escape apparatus the set is always ready for use there being no valve to operate to start the flow from the cylinder. Visibility was good and no undue resistance to breathing was experienced.

CA.2 Apparatus

This equipment was found to be comfortable in use, the high pressure hose was sufficiently flexible to allow reasonable head movement when wearing the mask which was however considered rather cumbersome and required adjustment of the suspension harness after donning. Resistance to breathing was considered acceptable.

CA.3 Apparatus

This set was regarded as a poor third choice by all the subjects. All found the wearing position (slung across front of chest) uncomfortable. The high pressure hose between mask and cylinder was too rigid and when head movements were necessary the face mask also being rigid, forced the head to swivel independently.

2.6 Series 5 Evaluation of closed and open circuit apparatus when worn by inexperienced wearers.

Following the general conclusions arrived at as a result of the bench pilot laboratory, and field investigation it was decided to conduct a series of tests of emergency escape equipment when worn by inexperienced wearers. The apparatus selected for these investigations were the CA.1 open circuit compressed air and OX.1 closed circuit oxygen apparatus.

A sample group of 24 sedentary workers employed in a central headquarters of a nationalised industry were selected as the subjects to be studied. The occupations covered included work study practitioners, purchasing officers and design engineers and were representative of working groups who as a result of the work could be visiting an engineering site and become involved in an emergency evacuation requiring the use of respiratory protection. The physical characteristics of the group are shown in Table 2.14. The ages ranged from 21 to 53 and they were grouped into four age ranges 18-28, 29-38, 39-48 and 49-58 years. Six subjects in each group. Purely by chance the subjects selected comprised 50% non smokers, three in each group of six.

2.6.1 Procedure and results Series 5 investigation

A series of 4 experiments were conducted using open circuit equipment CA.1 and closed circuit equipment OX.1.

Series 5.1 Open circuit equipment at 50 watt constant work rate

Series 5.2 Open circuit equipment at 50 watt constant work rate for 5 mins and increasing work load at the rate of 1 watt/minute until the equipment was exhausted.

Series 5.3 Closed circuit equipment as 5.1 above

Series 5.4 Closed circuit equipment as 5.2 above.

The method of test for 5.1 was identical to that used in Series 3.1 pilot Laboratory Tests. The observation made, however, were augmented by recording the number of respirations/minute and the pulse rate at the commencement and completion of each test.
For experiment 5.2 the work rate was increased after 5 minutes by using the facility in the cycle ergometer for continuously increasing the work load. The observed results of these experiments are shown in Tables 2.16 to 2.19 inclusive and the averaged results for each group and total group are shown in Table 2.15. The method of test for 5.3 and 5.4 above was identical to that used in Series 3.2 Laboratory tests.

GROUP	CODE	AGE years	WEIGHT Kg	HEIGHT m	CHEST CIRCUM. cm.	CAPACITY l *
1	RH	21	65.31	1.778	87.7	5.2
	JN	23	89.83	1.854	109.3	5.6
	TG	23	69.81	1.791	95.3	5.3
	VG	24	63.5	1.753	90.8	5.1
	AC	27	56.21	1.803	88.3	5.3
	EW	28	66.68	1.778	94.1	5.1
2	KB	30	72.08	1.778	95.3	5.1
	MT	33	75.32	1.727	100.4	4.7
	AB	33	59.98	1.791	89.5	5.1
	BT	35	67.81	1.816	91.5	5.2
	PC	37	69.81	1.796	92.7	5.0
	GC	38	75.32	1.778	94.6	4.9
3	LL	39	75.32	1.791	99.1	5.0
	KS	40	67.81	1.788	95.3	4.9
	AG	41	84.32	1.803	101.6	5.0
	DJ	42	76.2	1.788	93.3	4.8
	JR	44	65.31	1.721	93.3	4.5
	TU	45	83.87	1.788	96.5	4.8
4	TS	49	75.32	1.778	95.9	4.6
	JH	49	62.98	1.664	88.9	4.1
	TM	54	67.58	1.778	95.3	4.5
	RH	54	87.11	1.803	106.7	4.6
	LF	55	61.27	1.753	89.3	4.4
	JM	57	63.5	1.651	100.4	3.9
MEAN	1	24.3	68.56	1.7928	94.31	5.3
	2	34.3	69.05	1.7801	94.0	5.0
	3	42	75.47	1.779	96.5	4.8
	4	53	69.626	1.737	96.1	4.4
MEAN	TOTAL	38.4	70.68	1.772	95.21	4.85

TABLE 2.14 Subject Data - Physical Characteristics. Inexperienced wearers

*Vital Capacity taken from the nomograph prepared by Miller et alia(1959) for healthy adults.

The observations were however extended to include pulse rate at start and finish of the investigation and the work rate increases procedure for experiment 5.4 was similar to that used in experiment 5.2.

The observed results of these experiments are shown in Tables 2.21 to 2.24 inclusive and the averaged results for each group and total group are shown in Table 2.20.

The group sample was reduced by one in group 1 owing to the subject being unavailable. One subject in group 3 declined to undertake the increasing work rate evaluation and 2 subjects in group 4 declined both the constant and increasing work rate tests. Only one subject requested the test to be terminated, a group 2 subject requested both the constant and increasing work rate tests to be terminated after 14 minutes due to the temperature in the face mask. The only instruction to the subjects before the commencement of the test was to sit on the cycle ergometer, don the face mask and pedal, a number of questions were posed by subjects at the completion of test, discussion was, however, deferred until the full cycle of tests had been completed. No results on performance were given to the subjects.

After the completion of the final test, the results of each experiment was discussed with the subjects individually and subjective assessment was sought on their opinion of the equipment and method of test. The general consensus favoured the compressed air equipment and if given the choice all subjects would have selected the open circuit equipment. The main objection to the closed circuit equipment being the rise in temperature an average of 17.7^{o}C for constant work rate and 21.1^{o}C for increasing work rate tests.

During the Series 5.3 and 5.4 experimental work face mask leakage occurred with a Group 1 subject on constant work rate and one subject in Groups 2, 3 and 4 also experienced severe face mask

leakage during both the constant and increasing work rate tests. This was attributed to the design of the respirator face piece and frontal cavities in the forehead of the subjects Fig.2.10 show typical examples of these features.

As stated in Chapter I the point at which the apparatus will present the most serious problem is the seal between the face mask and the wearers face.

The use of full face masks with emergency escape apparatus is considered essential and the experiment carried out in the Series 5 investigation with inexperienced wearers emphasised the need for accurate methods to evaluate full face mask efficiency. It is generally accepted that all face masks leak to some extent; the leakage being past the peripheral seal to the wearers face this can be adversely affected by facial hair as reported by Longsen (1971) and Carter (1971). Movement of the head and of the facial muscles as well as concave areas of the face can also contribute to possible inward leakage.

Methods of evaluation of inward leakage have been described by Mounam(1962) Morgan (1964) using either a sodium chloride aerosol or a halogenated hydrocarbon gas in the atmosphere surrounding the mask. Burgess et al(1961) reported on the use of uranine and Guyton et al(1967) and Letts (1961) reported on the use of bacterial spores. A review of these methods indicated that they are not in general considered suitable for the rapid determination of inward leakage of gas into a full face mask.

The sodium chloride aerosol method has the disadvantage that particles are absorbed in the respiratory tract and that the subject must breathe regularly. There may be therefore difficulties in applying the method while subjects are exercising. Halogenated hydrocarbons have the disadvantage

of being mildly toxic so that the concentration in the trace gas atmosphere must be kept relatively low, the accuracy of the method may therefore be limited.

2.7 Series 6. Laboratory Test describes an evaluation of the inward leakage potential of the face masks used in the previous experimental work these having the following facial seal designs.

CA.1	Internal Roll
CA.2	Pneumatic
CA.3	Cushion
OX.1	Flat

The latter being only used with the closed circuit equipment. Face mask OX.2 was not evaluated as the design did not allow the required modification for this series of tests.

In addition to the differences in type of seal the masks selected for this study differed in other design features. To ensure that the observed test results for inward leakage were due to the difference in facial seals only and not other characteristics, the masks were modified to a common inhalation/exhalation system the visor, rubber moulding and head suspension being the only variables.

2.7.1 Procedure and Results. The test selected was the dynamic method developed at the Safety in Mines Research Establishment(SMRE) this has since been embodied in British Standards as a standard test method. Fig.2.11 Page 121 shows a schematic diagram of apparatus. The method required the subject to walk at 6.4 Km/hr on a tread mill wearing the face mask complete with breathing tubes, enclosed in a transparent plastic hood of sufficient size to allow movement of the head wearing the mask. Fig.2.12 Page 122 shows a subject under test.

Pure argon was fed into the top of the hood from a regulated cylinder supply at a rate sufficient to maintain the pressure just above atmospheric throughout the test.

The subject inhaled oxygen supplied from a cylinder fitted with a pressure reducer and a lung governed demand valve.

The coupling to the face mask was fitted with two non-return valves controlling the direction of flow of oxygen and exhaled gas in the breathing tubes. The exhaled gas was sampled, the amount of argon in the exhaled gas was determined by means of a mass spectrometer to give an accurate measure of the face mask inward leakage.

The tests were conducted on six clean shaven subjects for each face mask. In each test the subjects while on the treadmill carried out a series of prearranged head movements. The head movements were head steady (2 minutes) head side to side (2 minutes) head up and down (2 minutes) head steady but reading the alphabet out loud (2 minutes) and head steady (2 minutes). Total test duration 10 minutes.

The results of these tests are shown in Table 2.25 and show that the order of performance of the facial seal for inward leakage was

CA.2 (Fig 1.7) 0.005 to 0.011% or 46 to 114 ppm.

CA.1 (Fig.1.6) 0.009 to 0.015% or 94 to 155 ppm.

CA.3 (Fig.1.8) 0.011 to 0.019% or 115 to 189 ppm.

OX.1 (Fig.1.9) 0.015 to 0.041% or 147 to 413 ppm.

The various British Standards listed in Chapter 1 Section 1.2 require permissible inward leakage to be of the order of 0.05% (500 ppm) maximum.

It is likely that the fit of masks may be improved by very careful adjustment by the wearer, however in the case of emergency escape

apparatus to be used by inexperienced wearers the possibility of an effective facial sealing of the face masks must be considered.

There may also be exceptional cases where wearers who because of facial characteristics (Fig.2.10 Page 120 cannot be satisfactorily fitted with full face respirator masks.

Subjects	No.		6	6	6	6	Average
Age	years		24.3	34.3	42	53	38.4
Weight	'Kg'		68.56	69.05	75.47	69.626	70.68
Height	'm'		1.79	1.78	1.8	1.73	1.772
Chest	'cms'		94.2	94.0	96.5	96.1	95.21
Vital capacity	'l' +		5.26	5.0	4.78	4.5	4.85
Respiratory resistance (inhalation)	mmH_2O		27.94	27.94	27.94	27.94	27.94
Work Rate Watts	(a)		50	50	50	50	50
on ergometer scale	(b)		148	140	138	116.8	135.7
Volume exhaled litres	l	a	355.6	399.6	375.6	352	370.7
		b	393	413	399.3	371.6	394.37
Duration of cylinder	mins	a	14.78	17.16	15.95	13.75	15.362
		b	14.6	16.73	13.97	11.52	14.21
Minute volume exhaled l		a	15	12.5	13.83	12.16	13.37
litres (min)		b	15.16	16.6	14.83	19	16.39
Minute volume exhaled l		a	29.83	28.0	29.16	33.5	30.12
litres (max)		b	39.5	43.3	43	44	42.45
Minute volume exhaled l		a	24.03	23.39	23.65	26.72	24.44
litres (av)		b	26.94	29.43	28.94	32.55	29.468
Exhalation temperature	^oC	a	25.3	25.8	26	25.6	25.67
		b	24.6	22.6	24.8	23.8	23.95
Oxygen deficit	%	a	4.2	4.14	4.22	4.04	4.15
		b	5	4.76	4.5	4.8	4.765
Oxygen consumption	ml/min +	a	935	937	975	941	984
		b	2091	1999	2014	1729	1959
Carbon dioxide production	ml/min +	a	889	898	927	999	928
		b	1266	1312	1215	1464	1316
Total respirations		a	222.6	294.5	260.8	286	265.91
		b	172	257.3	215.8	232.6	217.9
Respirations/min (min)		a	12.83	15.5	14.6	18.33	15.31
		b	10.1	14.16	12.3	14.8	12.84
Respiration/min (max)		a	18.16	21.16	18.16	24.5	20.49
		b	15.16	20.3	20	26.4	20.46
Respirations/min (av)		a	15.08	17.36	16.65	17.78	16.71
		b	11.87	16.9	15.876	20.627	16.31
Pulse rate/min start		a	74.6	72.6	73.6	75.6	74.1
		b	72.6	76	73	74	73.9
Pulse rate/min finish		a	94.3	91.0	93.0	95.83	93.5
		b	100	100.6	103.3	102	101.75
Pulse rate/min increase		a	19.7	18.4	19.4	20.23	19.4
Hr			27.4	24.6	30.3	28	27.85
Respiratory quotation	+	a	.95	.958	.950	1.06	.979
		b	.60	.656	.603	.846	.676

\+ by calculation

'a' = Constant Work Rate (50 watts)

'b' = Increasing Work Rate

TABLE 2.15 Averaged results of CAI equipment

Code			RH	JN	TG	VG	AC	EW	MEAN	RH	JN	TG	VG	AC	EW	MEAN
Date (1970)			29/7	22/7	29/7	24/7	24/7	22/7	-	7/8	11/8	12/8	11/8	7/8	12/8	-
Work Rate	Watts	W	50	50	50	50	50	50	50	160	155	149	147	150	128	148
Total Volume	litres	l_t	383	362	395	275	376	343	356	407	419	378	373	424	361	393
Time	minutes	M	14.6	13.59	19.1	12	17	12.4	14.78	15.25	15.3	15	14.5	15.08	12.5	14.60
Minute Volume	litres	l_{min}	14	25	7	12	11	21	15	15	20	9	12	17	18	15.16
" "	litres	l_{max}	31	32	27	27	27	35	29.8	39	38	39	37	44	40	39.5
AV " Volume	litres	la_v	26.6	26.63	20.64	21.15	22.1	27.6	24.03	26.6	27.3	25.2	25.5	28.11	28.88	26.94
CO_2 max		%	3.4	4.5	3.2	4.3	4.0	3.3	3.78	4.4	4.5	4.3	4.3	4.5	4.0	4.3
Temperature		^0C	25	25	25	26	26	25	25.3	28	23	23	23	28	23	24.6
Total No.of Respirators		N_t	272	148	249	155	231	281	272.6	186	143	168	154	179	202	172
" " " "		N_{av}	18.54	10.8	13.01	11.92	13.58	22.63	15.08	12.19	9.3	11.2	10.56	11.86	16.16	11.87
Respiration/minute		R_{min}	25	11	11	12	12	16	12.8	12	8	9	9	9	14	15.16
" /minute		R_{max}	20	16	17	14	15	27	18.16	17	11	14	14	18	17	10.1
Pulse rate start		P_s	76	68	84	72	73	75	74.6	72	17	78	72	70	72	72.6
" " finish		P_f	100	86	104	88	94	94	94.3	104	96	104	100	108	92	100

TABLE 2.16. Observed Results. Group 1

50 watt Constant and increasing work rates on ergometer

Open Circuit Compressor Air Apparatus CA.1

Code			KB	MT	AB	BT	PC	GC	MEAN	KB	MT	AB	BT	PC	GC	MEAN
Date 1970			11/8	3/8	22/7	31/7	4/8	24/7	-	13/8	17/8	22/7	13/8	13/8	5/8	-
Work Rate	Watts	W_o	50	50	50	50	50	50	50	132	153	140	122	150	148	140
Total Volume	litres	l_t	425	454	308	413	411	387	399.6	406	423	433	407	405	404	413
Time	minutes	M	16.75	19.75	13.416	16.75	20.3	16	17.16	13.25	15.16	14.166	12.41	15.16	14.4	16.73
Minute Volume	litres	l_{min}	13	7	16	18	12	9	12.5	19	14	16	25	15	11	16.6
" "	litres	l_{max}	29	29	28	29	24	29	28.0	41	40	51	41	42	45	43.3
AV" "	litres	l_{av}	25.37	22.99	22.95	24.65	20.21	24.18	23.39	30.64	27.90	30.5	32.796	26.715	28.05	29.43
CO_2 max		%	3.4	3.2	3.2	3.2	4.5	3.2	3.45	4.5	4.6	3.9	4.0	4.7	4.6	4.38
Temperature		^oC	23	28	25	27	26	26	25.8	23	20	22	23	23	25	22.6
Total No of Respirators		N_t	300	367	253	310	244	293	294.5	223	226	333	236	191	215	237.3
AV " " "		N_{av}	17.91	18.58	18.86	18.5	12	18.31	17.36	16.83	14.90	23.5	19.01	12.5	14.93	16.9
Respirations/minute		R_{min}	16	18	19	18	10	12	15.5	15	11	21	17	11	10	14.16
" / "		R_{max}	19	20	22	22	16	18	21.16	19	20	27	21	14	21	20.3
Pulse rate starts		P_s	76	72	68	82	72	66	72.6	72	72	84	84	72	72	76
Pulse rate finish		P_f	88	98	80	96	88	96	91.0	100	96	100	104	100	104	100.6

TABLE 2.17. Observed Results. Group 2

50 watt Constant and increasing work rates on ergometer

Open Circuit Compressor Air Apparatus CA.1

Code			LL	KS	AG	DJ	JR	TU	MEAN	LG	KS	AG	DJ	JR	TU	MEAN
Date 1970			4/8	31/7	20/7	20/7	27/7	31/7	-	10/9	15/10	3/8	4/8	7/8	31/7	-
Work Rate	watts	W	50	50	50	50	50	50	50	150	152	156	143	118	110	138
Total Volume	litres	l_t	422	411	320	342	371	388	375.6	404	421	434	408	355	374	399.3
Time	minutes	M	17.59	17.75	15.5	16.55	15	13.25	15.94	15	15.3	16.5	14.3	11.75	11	13.97
Minute Volumes	litres	l_{min}	16	13	12	10	9	23	13.83	14	13	12	12	11	27	14.83
" "	litres	l_{max}	26	28	29	28	31	33	29.16	41	43	45	45	40	44	43
AV " "	litres	lav	23.986	23.15	20.6	20.2	24.73	29.28	23.65	26.9	27.45	26.3	28.4	30.6	34	28.94
CO_2 max		%	3.2	4.3	4.4	4.3	4.3	3.3	3.96	4.3	4.6	4.9	4.6	4.6	4.1	4.51
Temperature		^oC	26	27	25	25	26	27	26	20	25	28	26	28	22	24.8
Total No of Respirators		N_t	342	252	194	254	240	303	260.8	277	204	163	220	177	254	215.8
AV " " "		N_{av}	19.4	15	12.5	15	16	22	16.65	18.26	13.3	9.8	15.3	15.06	23.0	15.876
Respirations/min		R_{min}	17	13	11	12	14	21	14.6	16	10	6	9	13	20	12.3
" /min		R_{max}	20	15	15	18	17	24	18.16	21	20	16	20	17	26	20
Pulse rate start		P_s	68	72	72	70	84	76	73.6	72	68	72	70	78	78	73
" " finish		P_f	80	96	96	94	96	96	93	96	100	112	106	106	100	103.3

TABLE 2.18. Observed Results. Group 3

50 watt Constant and increasing work rates on ergometer

Open Circuit Compressor Air Apparatus CA.1

Code			TS	JH	TM	RH	LF	JM	MEAN	TS	JH	TM	RH	LF	JM	MEAN
Date 1970			26/7	29/7	3/8	20/7	26/7	10/8	-	17/9	17/9	10/8	5/8	10/8	14/8	-
Work Rate	Watts	W	50	50	50	50	50	50	50	95	130	140	118	98	98	116.8
Total Volume	litres	l_t	294	393	449	327	337	312	352	229	364	382	427	368	377	371.6
Time	minutes	M	13	17.16	19.5	10.5	11	10.3	13.57	9.75	13	14	11.43	9.58	9.6	11.52
Minute Volume	litres	l_{min}	7	9	17	16	11	13	12.16	12	13	17	23	17	25	19
Minute Volume	litres	l_{max}	28	28	26	38	41	40	35.5	30	40	40	49	42	49	44
AV Minute Volume	litres	l_{av}	22.6	22.8	23.02	31.1	30.63	30.20	26.72	23.48	28	27.285	36.34	32.15	39.0	32.55
CO_2 Max.		%	3.4	3.5	4.2	4.0	3.5	3.3	3.65	4.0	4.5	4.6	4.7	4.6	3.9	4.38
Temperature		^0C	25	26	28	26	25	24	25.6	23	23	24	25	24	23	23.8
Total No.of Respirators		N_t	301	383	283	205	261	283	286	232	266	203	201	213	280	232.6
AV " " "		N_{av}	23.1	22.3	14.5	19.5	23.72	27.3	17.78	23.79	20.4	14.5	17.106	22.23	28.9	20.627
Respiration/min.		R_{min}	21	19	12	18	18	22	18.33	21	15	13	12	13	21	14.8
Respiration/min.		R_{max}	25	25	17	20	27	33	24.5	25	24	26	23	26	33	26.4
Pulse rate start		P_s	76	78	76	76	76	72	75.6	80	76	72	78	72	72	102
" " finish		P_f	78	104	96	87	104	96	95.83	100	100	100	102	104	104	32.555

TABLE 2.19. Observed Results. Group 4

50 watt Constant and increasing work rates on ergometer

Open Circuit Compressor Air Apparatus CA.1

Subjects	No.	5	6	6	4	Average
Age	Years	25	34.3	42	53	38.57
Weight	Kg	69.20	69.05	75.47	69.73	70.86
Height	m	1.7958	1.7801	1.779	1.748	1.775
Chest	cms	96.105	94	96.52	95.05	95.41
Vital capacity + 'l'		5.26	5.0	4,78	4.5	4.85
Respiratory resistance (I)mm H_2O (crack)		25	25	25	25	25
Work Rate watts	a	50	50	50	50	50
On ergometer	b	160.2	153.3	145	132.5	147.75
Volume O litres	l a	42	42	42	42	42
	b	42	42	42	42	42
Duration of set min	M a	20.71	20.81	17.9	19.79	19.8
	b	16.06	15.47	14.53	13.35	14.85
O concentration min	% a	29.2	30.8	35.1	30.75	31.46
	b	40.4	29.8	29.2	33.75	33.34
O concentration max	% a	84.6	82.16	79.8	85.25	82.95
	b	83.4	85.5	88.0	85.25	85.53
Gas temperature min	°C a	22.4	23.1	23.3	23	22.95
	b	21	23.1	22.2	23	22.32
Gas temperature max	°C a	40.6	41.6	40.5	40.25	40.63
	b	44	44	42.8	42	43.2
Temperature rise	a	17.8	18.5	17.2	17.25	17.68
	b	23	21.9	20.6	19	21.125
CO_2 max %	a	2.1	2.8	2.2	2.6	2.4
	b	2.6	2.3	2.4	2.5	2.45
Pulse rate/min start	a	70.4	72.5	69.6	73.5	71.5
	b	72.8	72.6	71.6	73	72.5
Pulse rate/min finish	a	92	98.1	97.3	102	97.35
	b	115.4	116.3	113.2	113.5	114.52
Pulse rate/min increase	a	21.6	25.6	28	28.5	25.92
	b	42.6	43.7	41.8	40.5	42.15

TABLE 2.20 Averaged results of OX1 equipment

'a' = Constant work rate (50 watts)

'b' = Increasing work rate

Code	RH	JN	TG	VG	AC	EN	MEAN	RH	JN	TG	VG	AC	EW	MEAN
Date 1970	NOT AVAILABLE	22/10	13/10	19/10	19/10	7/10	-	NOT AVAILABLE	26/10	27/10	27/10	21/10	21/10	-
Work Rate Watts W		50	50	50	50	50	50		164	160	165	164	148	160.2
Total Volume Litres l		42	42	42	42	42	42		42	42	42	42	42	42
Duration minutes M		23.6	20.61	21.75	25.55	12.08*	20.71		16.25	16.66***	16.5	16.25	14.66	16.06
Oxygen Max. %		88	83	82	82	88	84.6		84	84	86	80	83	83.4
Oxygen Min %		31	29	30	29	27	29.2		41	40	38	41	42	40.4
Temperature Start $^{o}C_s$		22	24	22	22	22	22.4		21	21	21	21	21	21
Temperature Finish $^{o}C_f$		42	41	40	42	36	40.2		45	44	43	45	43	44
Pulse Rate Start P_S		68	72	72	72	68	70.4		72	74	70	72	76	72.8
Pulse Rate Finish P_f		86	102	88	96	88	92		116	109	120	120	112	115.4

TABLE 2.21. Observed Results. Group 1

50 watt Constant and Increasing Work Rates on ergometer

Closed Circuit Oxygen Apparatus OX.1

* Face mask leak
** Test terminated by subject
*** Under pedalled.

Code			KB	MT	AB	BT	PC	GC	MEAN	KB	MT	AB	BT	PC	GC	MEAN
Date			13/10	21/10	15/10	22/10	14/10	7/10	-	26/10	27/10	26/10	29/10	27/10	26/10	-
Work Rate	Watts	W	50	50	50	50	50	50	50	158	158	148	155	169	** 132	153.3
Total Volume	litres		42	42	42	42	42	42	42	42	42	42	42	42	42	42
Duration	minutes	M	20.3	24.16	* 16.36	23.25	** 14.0	20.81	15.91	15.6	** 14.91	15.5	16.91	** 14		15.47
Oxygen max.		%	88	84	80	82	87	72	82.16	88	88	73	88	87	89	85.5
" min.		%	32	28	33	28	26	38	30.8	28	29	30	28	28	36	29.8
Temperature start		$^{o}L_{s}$	24	23	24	23	23	22	23.1	23	23	23	23	24	23	23.1
Temperature finish		$^{o}C_{f}$	42	43	38	42	44	41	41.6	46	42	42	44	47	43	44.0
Pulse Rate Start		P_{s}	73	72	68	78	72	72	72.5	74	72	70	76	68	76	72.6
Pulse Rate finish		P_{f}	103	98	88	100	98	102	98.1	128	118	104	120	112	114	116.3

TABLE 2.22. Observed Results. Group 2

50 watt Constant and Increasing Work Rates on ergometer

Closed Circuit Oxygen Apparatus OX.1

* Face mask leak
** Test terminated by subject
*** Under pedalled.

Code	LL	KS	AG	DS	JR	TU	MEAN	LL	KS	AG	DJ	JR	TU	MEAN
Date 1970	15/10	15/10	5/10	1/10	5/10	15/10	-	27/10		28/10	28/10	27/10	27/10	-
Work Rate Watts W	50	50	50	50	50	50	50	149		148	150	132	146	145
Total Volume litres	42	42	42	42	42	42	42	42		42	42	42	42	42
Duration minutes M	17.91	17.93	17.41	18.41	13.83*	21.95	17.9	14.91		14.91	15.0	13.25*	14.91	14.53
Oxygen Max %	86	84	76	76	68	89	79.8	88		88	89	87	87	88
Oxygen Min. %	32	33	43	40	25	38	35.1	28		30	31	29	28	29.2
Temperature Start $^{o}C_{s}$	23	23	23	24	23	24	23.3	23		22	22	21	23	22.2
Temperature Finish $^{o}C_{f}$	42	41	42	42	35	41	40.5	43		42	43	42	44	42.8
Pulse Rate Start P_{S}	68		68	70	68	68	69.6	68		78	72	72	68	71.6
Pulse Rate Finish P_{f}	88	100	96	94	104	102	97.3	114		110	114	120	108	113.2

DECLINED TEST.

TABLE 2.23. Observed Results. Group 3

50 watt Constant and Increasing Work Rates on ergometer

Closed Circuit Oxygen Apparatus OX.1

* Face mask leak.

Code	TS	JM	TM	RH	LF	JM	MEAN	TS	JH	TM	RH	LF	JM	MEAN
Date 1970		12/10	13/10	5/10	7/10				22/10	20/10	20/10	20/10		
Work Rate Watts W		50	50	50	50		50		142	153	97	138		132.5
Total Volume litres		42	42	42	42		42		42	42	42	42		42
Duration minutes M		22.08	23.45	13.5	20.16		19.79		14.3	15.3	13.8	13.8		13.35
Oxygen max. %		86	82	88	85		85.25		86	84	87	84		85.25
Oxygen min. %		30	32	28	33		30.75		30	28	48	29		33.75
Temperature Start $^{o}C_{s}$		22	24	24	22		23.0		22	23	23	23		23.0
Temperature finish $^{o}C_{s}$		41	42	36	42		40.25		44	44	36	44		42.0
Pulse Rate Start P_{s}		78	68	72	76		73.5		76	76	74	72		73
" " Finish P_{f}		104	102	100	102		102		116	112	106	120		113.5

DECLINED TEST

DECLINED TEST

DECLINED TEST

TABLE 2.24. Observed Results. Group 4

50 watt Constant and Increasing Work Rates on ergometer

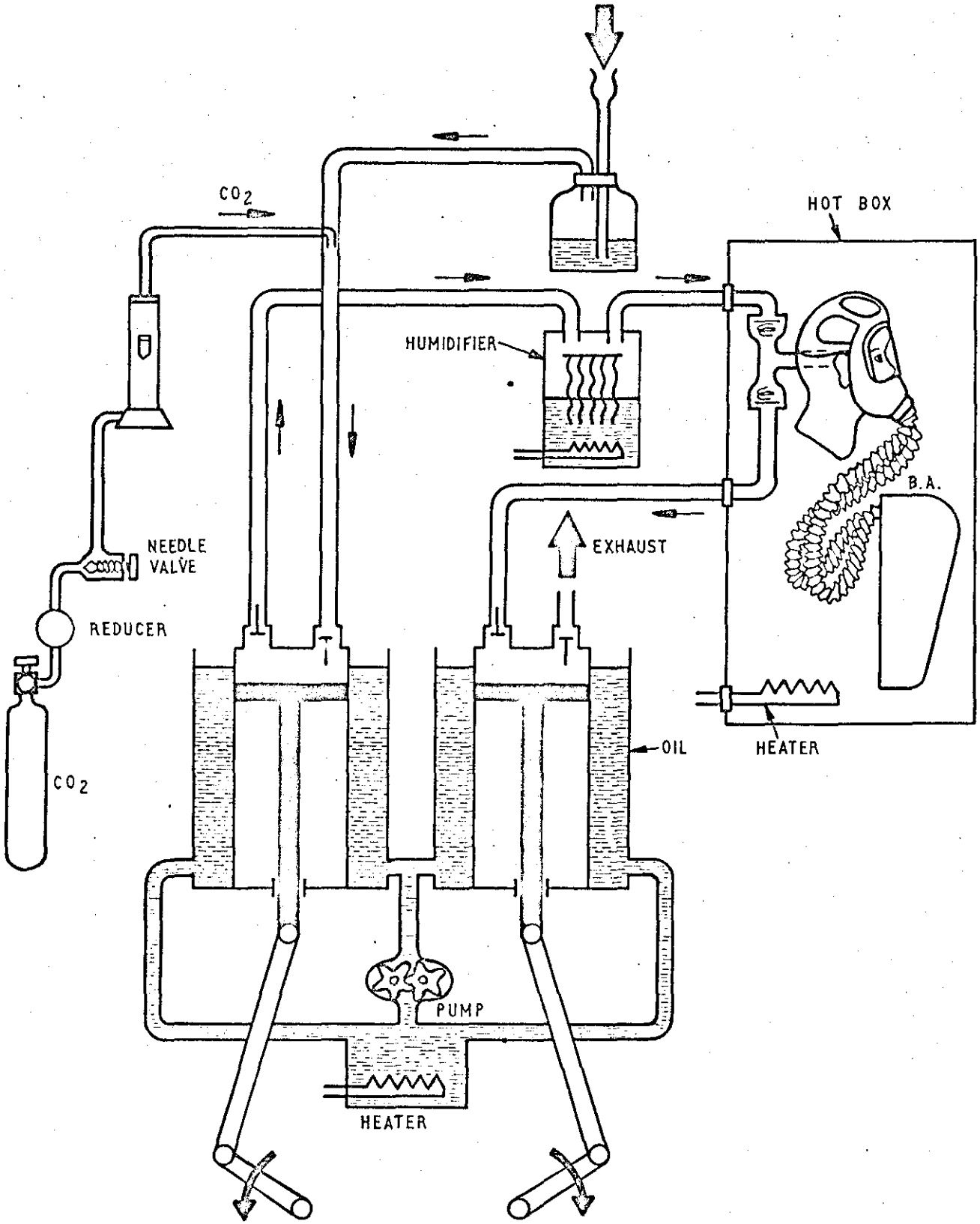
Closed Circuit Oxygen Apparatus OX.1

* Face mask leak.

Mask Identification	Subject No.	Leakage: p.p.m.						
		Steady	Head movements			Steady	Average	
			Side to Side	Up and Down	Steady and Talking		p.p.m.	%
C.A.1	1	155	125	217	151	122	154	.015
	2	241	100	85	222	128	155	.015
	3	69	75	71	52	63	97	.010
	4	62	217	142	250	58	145	.014
	5	105	94	85	100	100	96	.010
	6	132	45	80	90	127	94	.009
C.A.2	1	82	77	74	100	73	81	.008
	2	82	35	42	50	86	75	.007
	3	96	40	33	59	92	79	.008
	4	105	94	85	100	111	114	.011
	5	65	35	42	50	42	46	.005
	6	86	64	64	86	63	72	.007
C.A.3	1	140	130	67	255	131	159	.016
	2	104	83	410	99	94	189	.019
	3	86	64	64	86	88	115	.011
	4	49	90	172	271	56	127	.013
	5	188	136	119	150	123	143	.014
	6	146	125	119	237	135	181	.018
OX.1	1	414	376	387	379	368	388	.039
	2	220	191	196	198	186	275	.027
	3	110	81	84	96	90	147	.015
	4	411	316	262	300	287	315	.031
	5	111	192	204	312	108	185	.018
	6	461	442	366	392	406	413	.041

TABLE 2.25 Observed Results of Dynamic Leakage test

Mean	C.A.1	123 ppm	0.0123%
	C.A.2	77 ppm	0.0077%
	C.A.3	165 ppm	0.0165%
	OX1	287 ppm	0.0287%



C.E.G.B.	S.E. REGION
BREATHING MACHINE.	
Fig. 2.1	S.E.R. 632/10

ISSUE	A
7.72	

GRAPH OF FLOW LITRES/TIME OX.1 AND OX.2

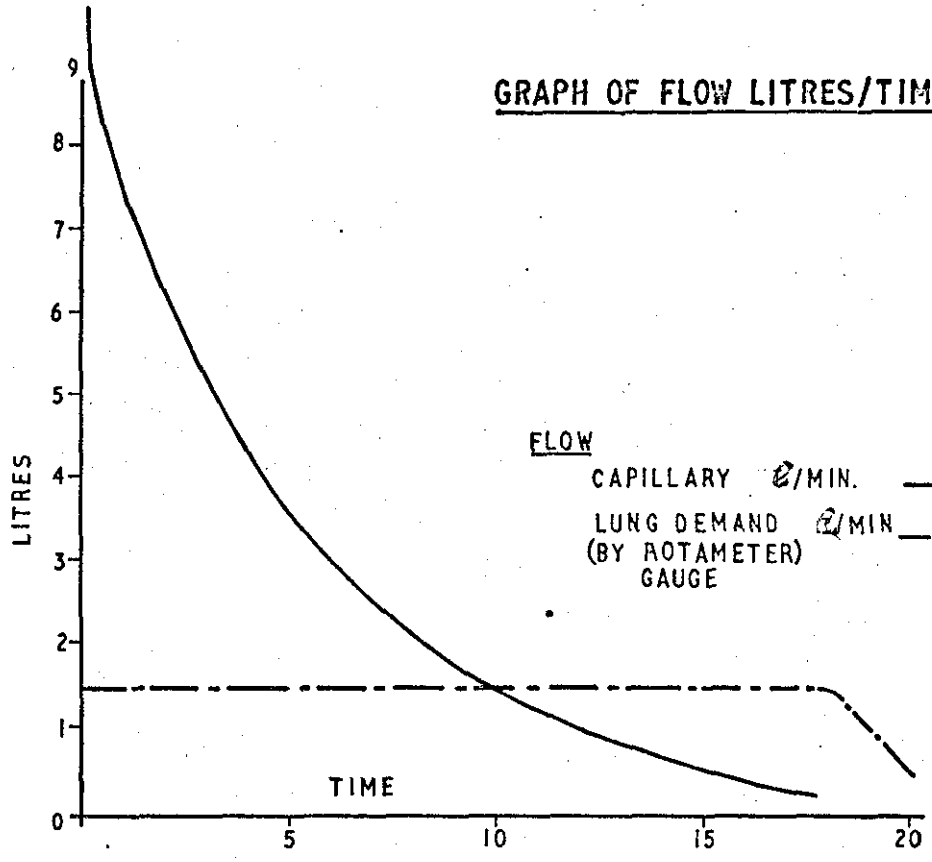


FIG 2.2

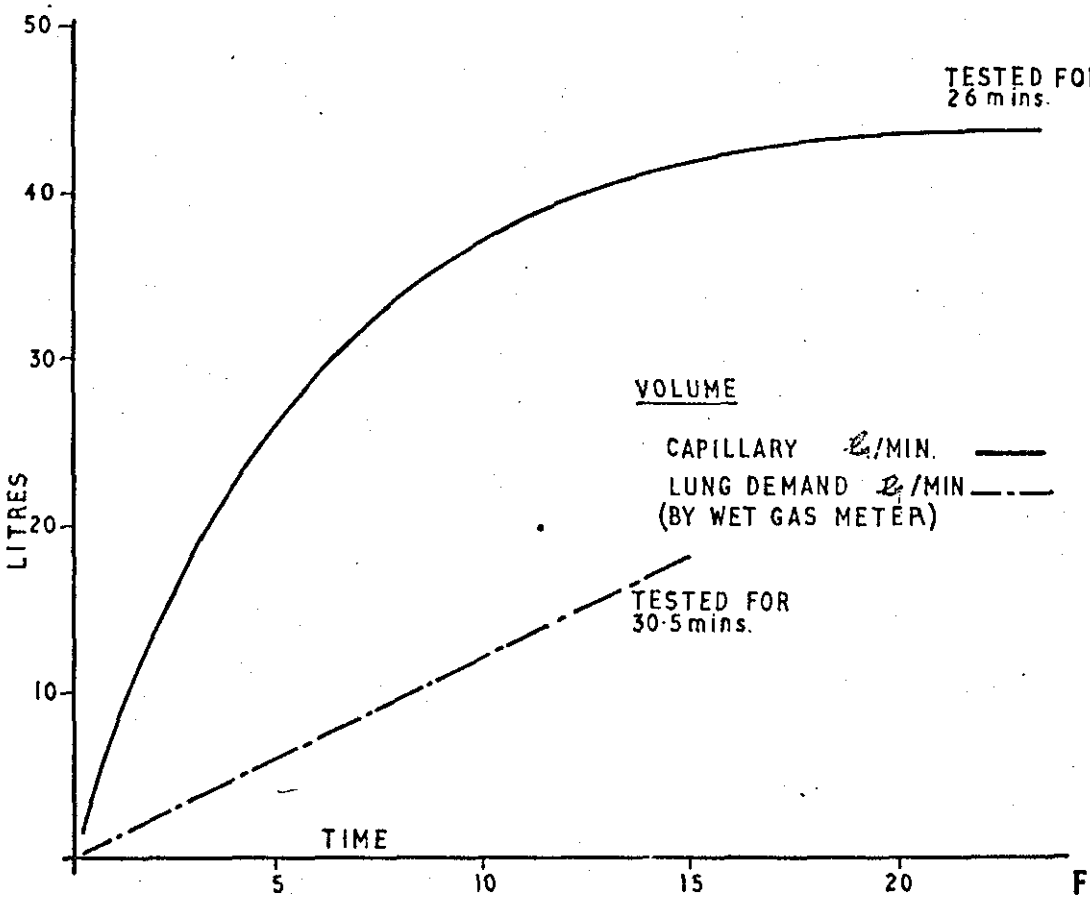
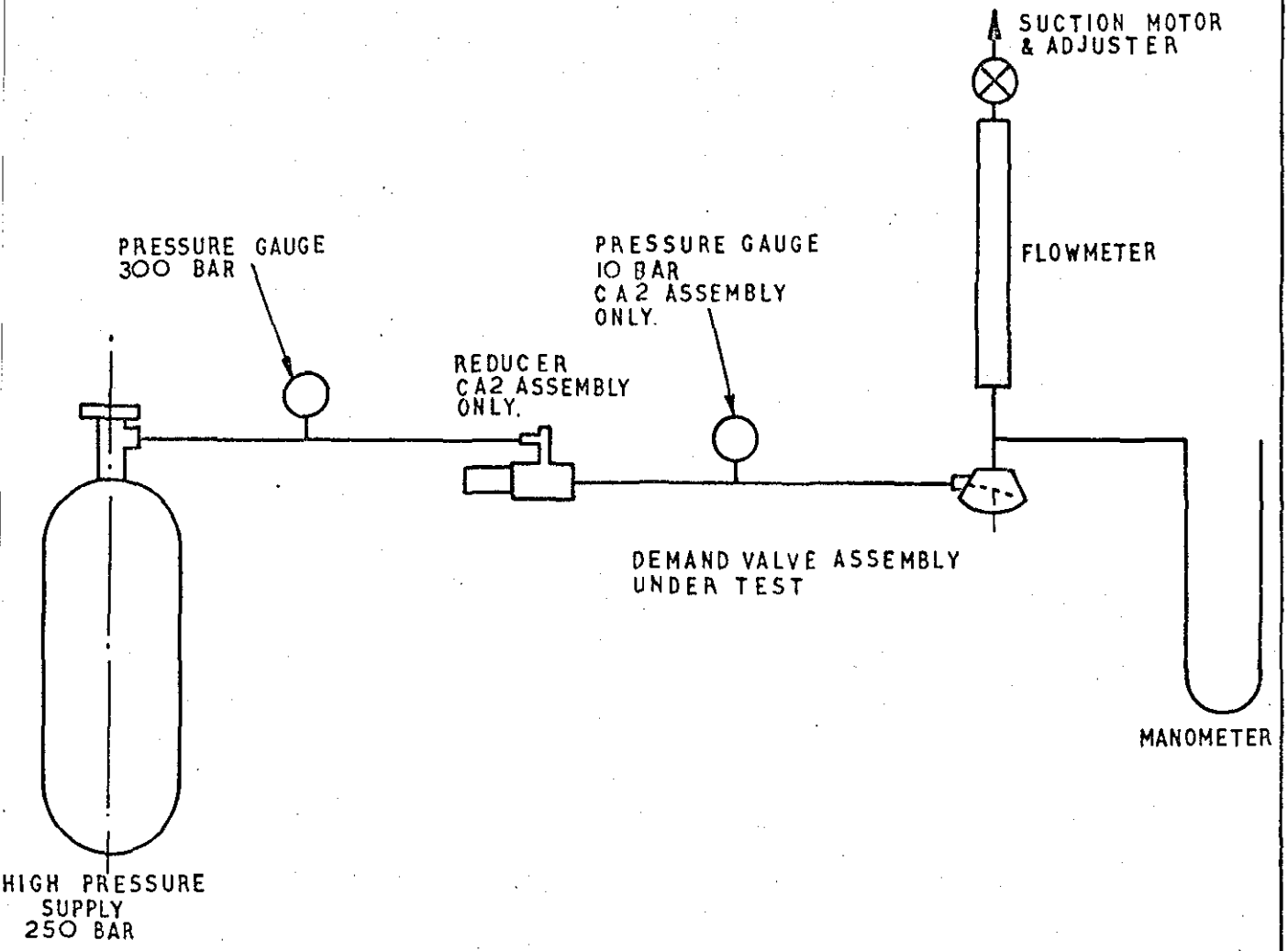
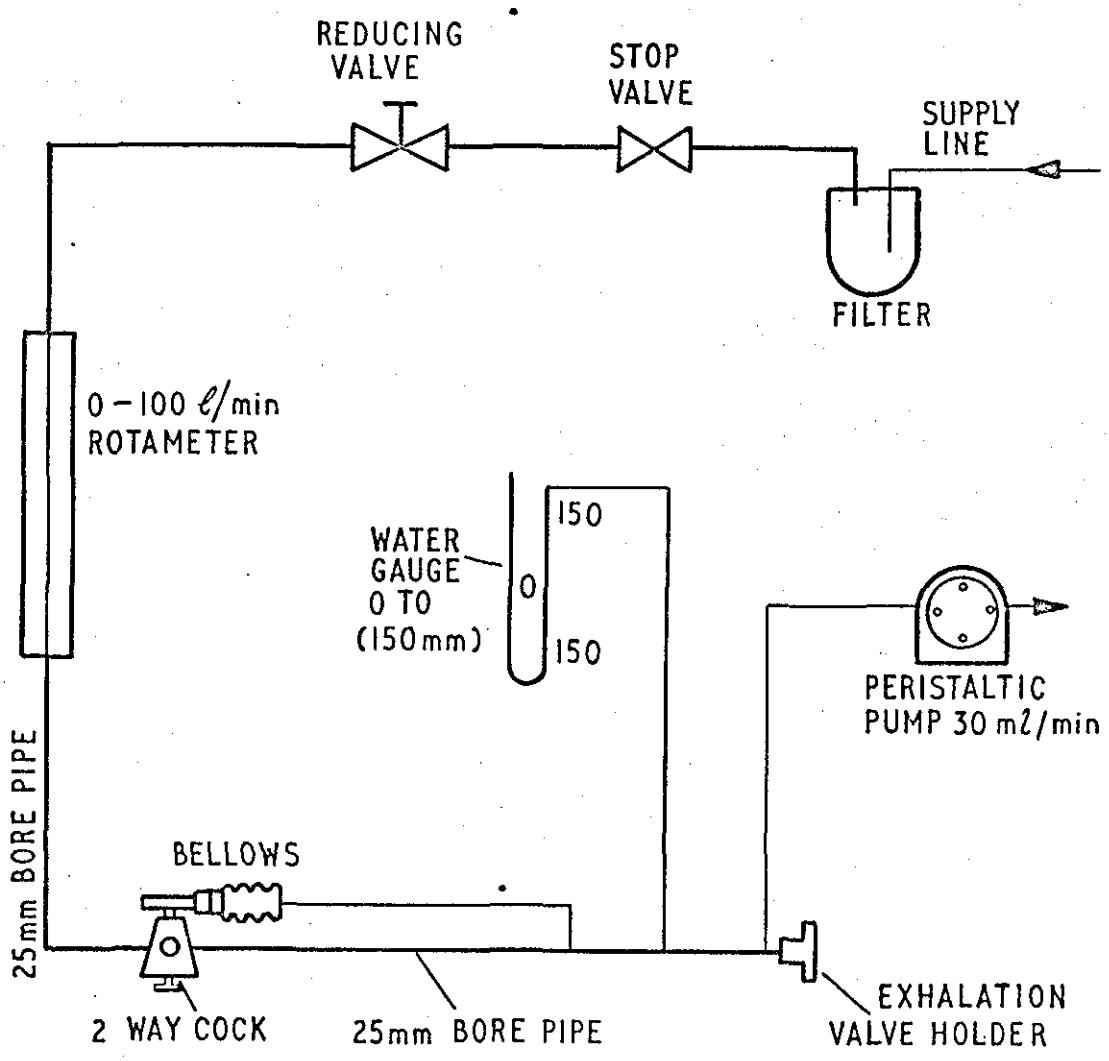


FIG 2.3

GRAPH OF VOLUME LITRE/TIME OX.1 AND OX.2



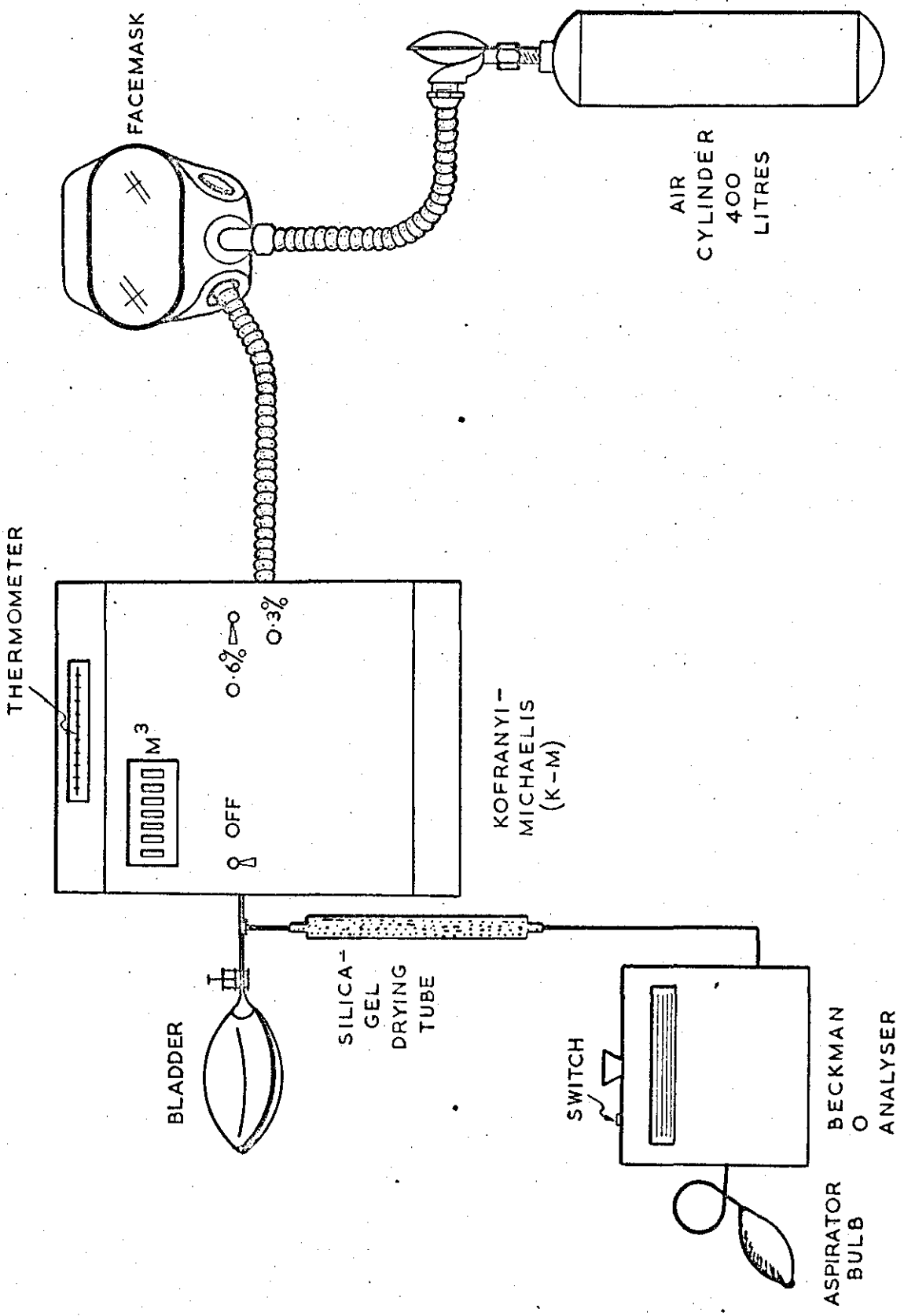
C.E.G.B.	S.E. REGION
SCHEMATIC DIAGRAM OF EQUIPMENT LAYOUT FOR DEMAND VALVE ASSEMBLY RESISTANCE MEASUREMENT.	
FIG 2.4	SER/632/12



C.E.G.B. S.E. REGION

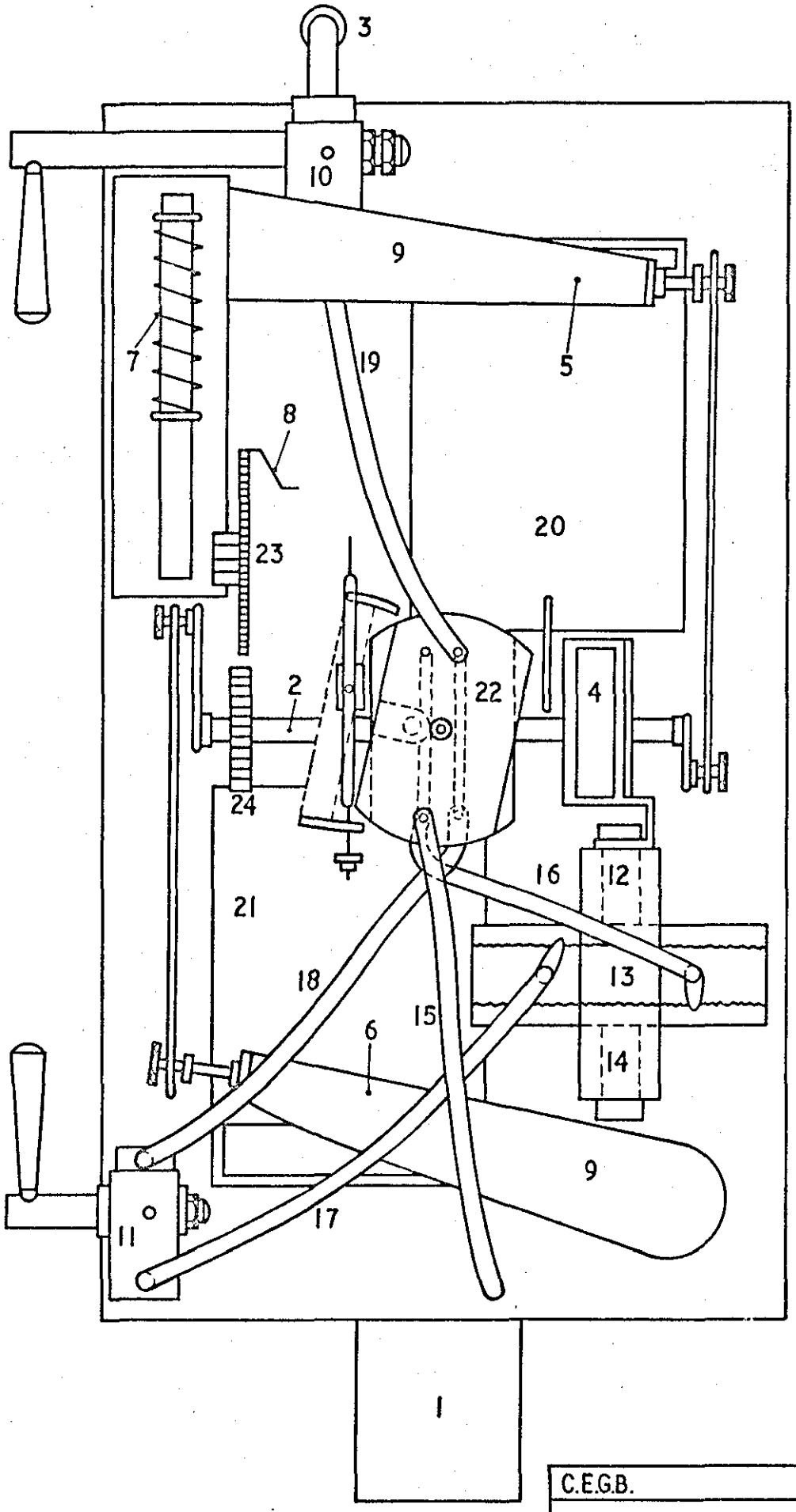
SCHEMATIC DIAGRAM EXHALATION VALVE ASSEMBLY RESISTANCE MEASUREMENT

1ST ISSUE 1·4·73	A	FIG 2.5	S.E.R. 632/16



CEGB	S.E. REGION
SCHEMATIC DIAGRAM SHOWING ARRANGEMENT OF EQUIPMENT USED FOR WORK RATE EVALUATION OF OPEN CIRCUIT BREATHING APPARATUS	

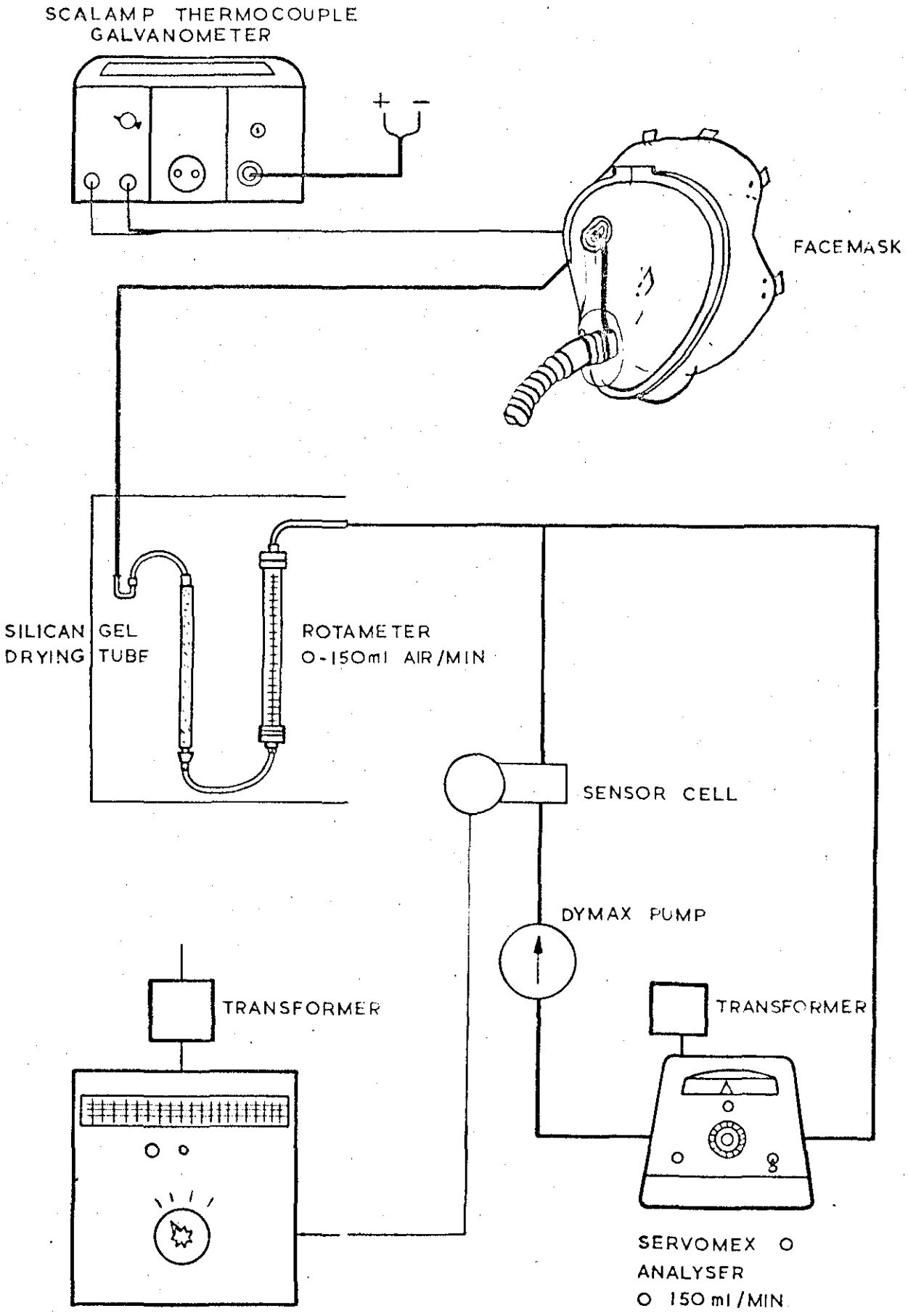
1st. ISSUE	A		Fig 2.6	SER 632/7
10. 7. 72.				



C.E.G.B. S.E. REGION

KOFRANYI MICHAELIS
RESPIRATION GAS METER MODEL 59
AS MODIFIED BY MÜLLER AND FRANZ.

t. ISSUE	A		Fig. 2.7	S.E.R. 632/9
.7.72				



CEGB	S.E. REGION
SCHEMATIC DIAGRAM SHOWING ARRANGEMENT OF EQUIPMENT USED FOR WORK RATE EVALUATION OF CLOSED CIRCUIT BREATHING APPARATUS	

t. ISSUE	A		
0. 7. 72.		Fig. 2.8	SER 632/8

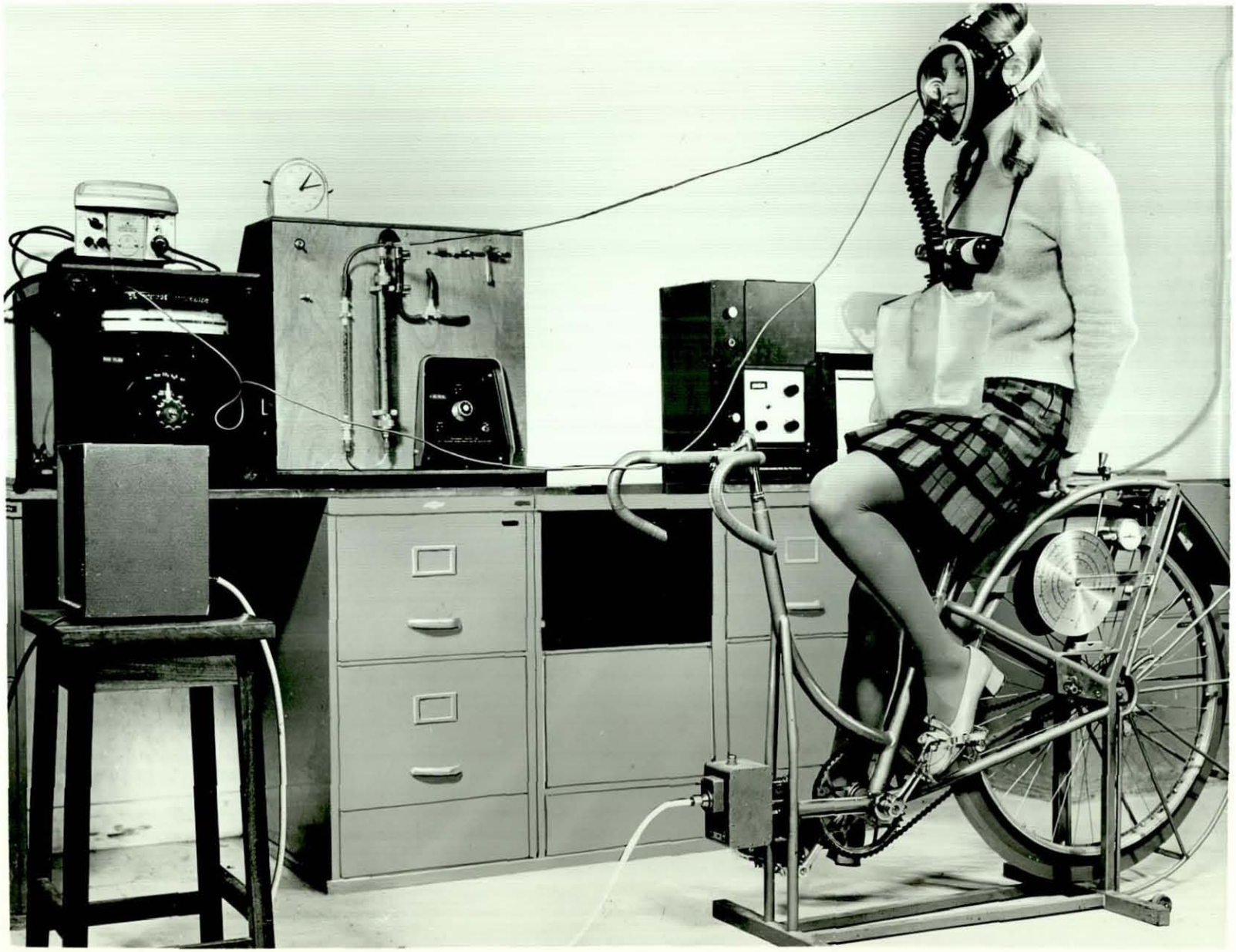
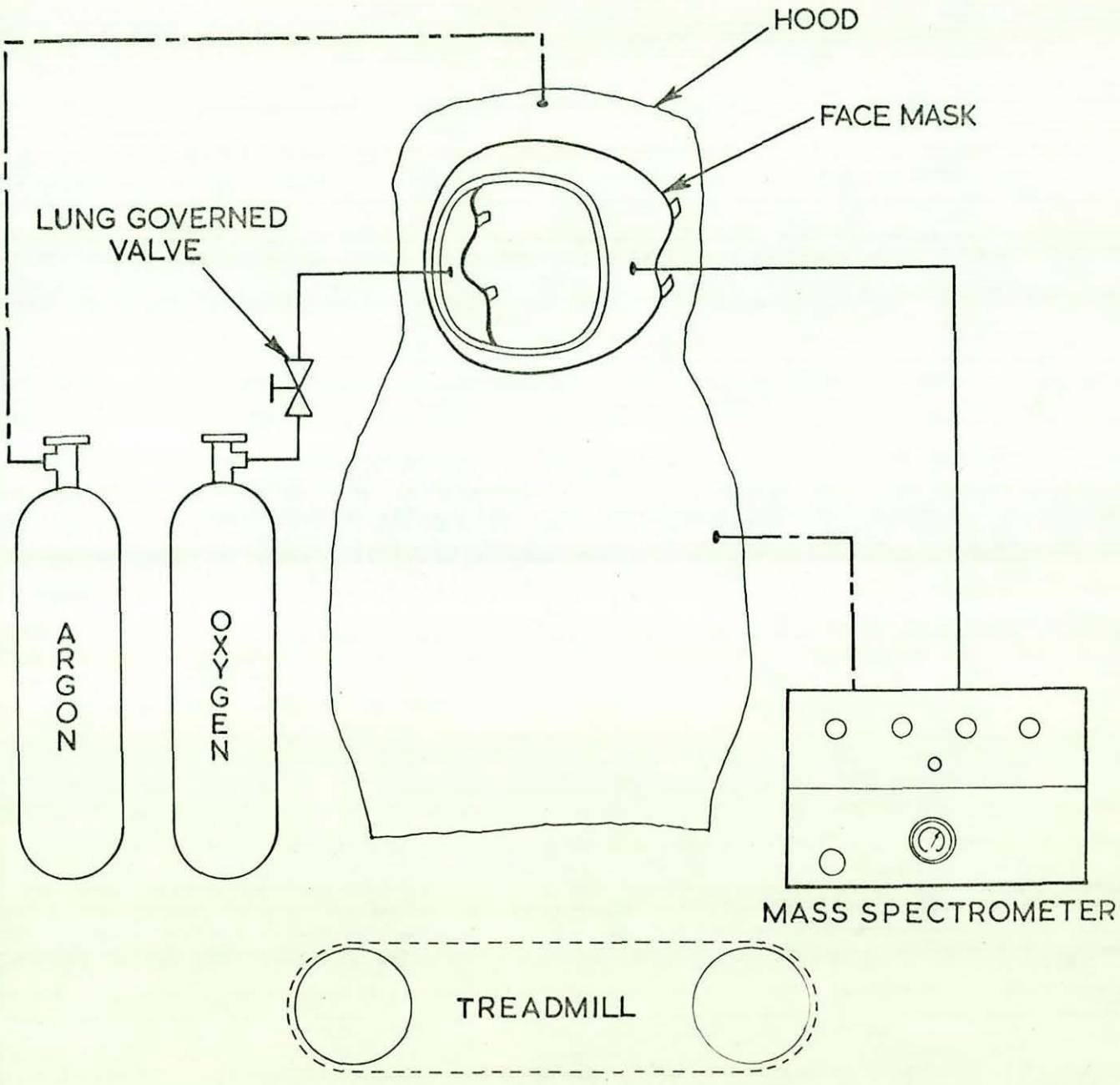


FIG. 2.9 SUBJECT UNDER TEST - WORK RATE EVALUATION OF OX.I EQUIPMENT

FIG.2.10 Subjects with forehead cavities which present problems for satisfactory facial seal with full face respirators.



C.E.G.B. S.E. REGION

SCHEMATIC DIAGRAM – ARRANGEMENT OF EQUIPMENT USED FOR INWARD LEAKAGE EVALUATION OF FACE MASKS

7.3.73	A	Fig. 2.11	SER 632/14

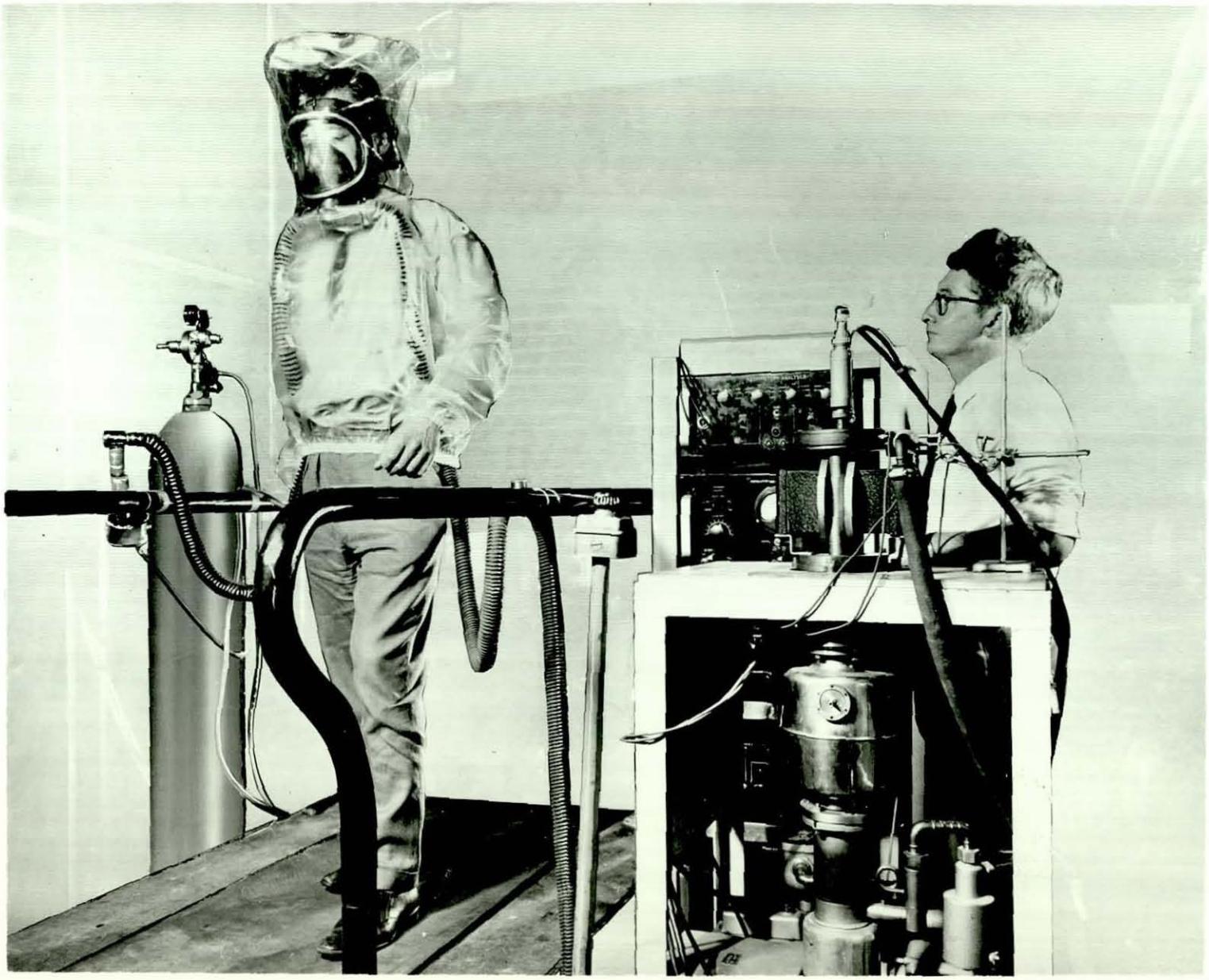


FIG. 2.12 SUBJECT UNDER TEST INWARD LEAKAGE

CHAPTER 3

DISCUSSION

INTRODUCTION

3.1 The history of self contained breathing apparatus dates back to 1852 when Schwann devised a portable apparatus for a prize competition of the Belgian Academy of Science and exhibited it during an Industrial Fair in Belguim. About 1880 the original Fluess apparatus was designed by H A Fluess Engineering(1933) and in 1903 the first Dreager apparatus was designed and manufactured by Bernhard Dreager of Lubeck Germany. The historical development of respiratory protection devices has been extensively recorded by Davis(1948).

The first comprehensive reviews of breathing apparatus appeared in reports by Haldane(1913-14) and (1914-15) and Henderson and Paul(1917). These reports drew attention to the serious defects and limitations of the apparatus then in use for mine rescue operations and also reported, were the inherent limitations of breathing apparatus and suggested improvements in design that would more readily meet the requirements of use in poisonous or irrespirable gases. All these reports established certain criteria whereby apparatus should be judged, and these have formed the basis of present day standards used in the United Kingdom and USA as stated in Ministry of Power Testing Memorandum No 3(1963) and US Bureau of Mines Federal Regulations(1970).

3.2 Recent reports have been made on the consideration of requirements existing designs and developments by the following:-

Marshall(1962) summarised the performance records of some existing types of breathing apparatus and the ways in which these performances fell short of desirable standards. Detailed suggestions were made of the standards which should be aimed at and which could be reasonably achieved, the design of a liquid oxygen breathing apparatus known as SIMBAL is discussed with respect to the desirable criteria for a two

hour closed circuit breathing apparatus.

Graham Jones (1962) showed that owing to the diversity of processes involved in the iron and steel industry a number of atmospheric contaminants arise, their varying toxic effect is discussed, suitable types of breathing apparatus and respirators are described for use in situations where control at source is not always possible.

Lavenne and Leyh (1962) compared the performance of four breathing apparatus three closed circuits and one open circuit design under elevated temperature conditions with nine trained subjects who were acclimatised to high temperature working for mine rescues. The result of these comparative studies favoured the open circuit design as the appratus provided much cooler inspired gas and suggested it should be used in preference to the closed circuit designs when rescue work could be performed near a compressed air line.

Shirling(1962)outlined the requirements of the Fire Service and stated that existing apparatus had proved satisfactory and reliable in use but there was much scope for improvement and made a special point on the temperature of the inspired gas on closed circuit sets. Although liquid air and oxygen can reduce this temperature these type of equipments are not available for immediate use under emergency conditions.

Berger et al(1963)reported on the use of breathing apparatus used in working situations at elevated air pressures such as in caissons or tunnel driving in subaqueous strata. The paper discussed, the physiological effects of gases at elevated temperature, the use of respiratory protective equipment in rescue operations in the event of fire or other emergency in pressurised tunnels and the effect of elevated pressure on performance of some gas detecting instruments. The paper also describes a procedure for controlling the partial pressure

of oxygen in the breathing circuit of an apparatus by initial dilation with nitrogen from normal air.

Morrison et al (1965) Reported on the comparison made between the physiological reactions of men wearing three types of breathing apparatus two closed circuit oxygen and one closed circuit liquid oxygen designs. They reported that from a physiological point of view the latter set was the most suitable type to be worn on rescue operations underground. The cooler air supplied by this set being an advantage in severe environmental temperatures.

Didenko and Shevchenko(1966) Reported on the common requirements for self contained breathing appliances and self rescuers in the USSR. It is difficult to make comparisons between standards that are based on different methods of test but it would appear that these are comparable with UK requirements.

Cretin(1967) Evaluated by practical testing with a team of eight rescue men the performance of 4 short duration equipments that were available on the European market and although found satisfactory suggested that the results of his investigation should be supplemented by laboratory studies.

Klauer(1967) Reported on the development, use and field experiences of filter type self rescuers and a self contained oxygen generating self rescuer of continental manufacture. This latter equipment on review appeared to offer many advantages to this research thesis but unfortunately attempts to obtain equipments for evaluation proved both difficult and expensive.

Kloos & Raymond(1968) reported on the low temperature of a four compressed air open circuit apparatus approved by US Bureau of Mines. Duration, breathing resistance and air flow rates were measured as bench tests

at room temperature and -25°F. Man tests under actual wearing conditions verify these results. It was found that many functional changes in apparatus performance occurred at low temperature.

Kloos and Beckert(1968) reported on the performance of two self contained closed circuit apparatus at 32 to -25°F. Low temperature effects of oxygen and carbon dioxide content in the breathing circuit visual properties of the facepiece and mechanical operation of the apparatus were studied. Although operation varied with the wearer, the breathing rate the apparatus re-cooling time and the temperature results, suggested that general use of currently available compressed-oxygen closed circuit apparatus be limited to temperatures above 32°F.

Griffin(1968) reviewed the physiological requirements which should be fulfilled for self contained closed circuit breathing apparatus used in rescue and recovery work in mines and compared and discussed the prescribed standards for approval of this equipment in various countries. A number of apparatuses currently available in Western Europe are described. It is suggested that the liquid oxygen type of apparatus has decided advantages over any other type.

3.3 Experimental Results of this study were to assess some of the physiological effects of wearing closed and open circuit breathing for self rescue when worn by inexperienced wearers.

The results of the experiments in this study are now discussed further with particular reference to, resistance to breathing, condition of respirable gas, effective duration face mask performance and wearer comfort.

3.3.1 Resistance to breathing In all types of respiratory protective apparatus the resistance to flow of the external circuit imposes an additional burden on the wearers respiratory system.

3.3.1.1 Closed Circuit The total resistance to respiration offered by a closed circuit breathing apparatus is stated in Section 1.5 as imposing upon the wearer a physiological burden due to the resistance offered by the breathing circuit.

This total resistance is made up of both frictional and elastic components. The frictional resistance is offered to the movement of air by the system of tubes and valves. The elastic resistance is provided by the breathing bag and is also effected by the pressure at which the gas is allowed through the relief valve.

Marshall(1962)suggested that if work rates were not high(and a minute volume of 50 litres maximum was postulated), that it is possible for a wearer to breathe against quite high pressures without coming to any harm but doing so could be considered to be unpleasant.

Studies by Hart(1943)and Silverman et al(1951)observed the responses at various measured resistances and work rates. From an examination of these recorded results Hartnell and Senneck(1956)suggested a maximum resistance standard for breathing apparatus. This was that the total dynamic resistance of an apparatus at a constant flow of 85 l/min should not be more than 60mmH_2O. Silvermans work also showed that resistances should be defined on both the inspiratory and expiratory sides of the apparatus since within the range of resistances experienced in existing equipments expiratory resistance was the more uncomfortable. At very low total resistances however, the balance of inspiratory to expiratory resistance is of little importance and it was suggested that the resistance of each side of the circuit at a constant flow of 85 l/min should not be more than 30mm H_2O ie half the suggested total.

It appears from a review of some of the literature that measurements of the resistance of a breathing apparatus under evaluation was taken only at one constant flow rate of 85 l/min this being roughly based

to the peak flow which would be produced by a man walking at three miles/hr.

It is recognised that measurement of resistance for the type of equipment under review at this single work rate was not sufficient and in the results of bench tests reported in Table 2.1 sinusoidal flow rates of 40, 80, and 100 l/min were used. British Standard 4667 part 1 1971 published since these tests were completed requires a laboratory performance test of the apparatus to be conducted on a breathing machine operating at a rate corresponding to 20 ventilations/min at a tidal volume of 2 litres the total delivery therefore being 40 l/min. This test to run for a period equal to the effective duration of the apparatus. Ina separate test the sinusoidal air flow is increased to 100 l/min for a period sufficient to assess the functioning of the breathing circuit at this flow rate. Also resistance to breathing on the inspiratory or the expiratory side of the circuit with the relief valve and breathing bag removed should have a dynamic resistance of not more than 30mmH_2O @ 125 l/min and 160 mm H_2O @ 300 l/min.

In addition to the dynamic resistance account must also be taken of the energy necessary to overcome the elastic forces of the closed circuit. The amount of energy necessary to operate the breathing bag (counter lung) depends upon the weight and flexibility of the material used and on its shape and mounting. It is considered however that a well designed bag makes only a very small contribution to the total amount of respiratory resistance. The amount of respiratory work experienced in operating the relief valve must however receive special consideration as this is performed at the end of expiration when it is subjectively most unpleasant and undesirable. Whilst it is desirable that the operating pressure of a relief valve should be as low as possible to minimise unpleasant subjective effect it is also necessary

for the pressure to be high enough to ensure that the breathing bag is fitted for all the anticipated work rates: As the air passes through a relief valve at high transient flows the resistance to this flow should once open be as low as possible. To meet the requirements on breathing apparatus for use by inexperienced wearers this should be an automatic operation and it is suggested should not exceed 50 mm H_2O.

Another area of resistance in the breathing circuit is the carbon dioxide absorber unit. The design of the absorber unit must be a compromise between the needs of low resistance and of high chemical efficiency. These are essentially antagonistic. The minimum resistance is obtained by the use of a very wide and very shallow cylinder and the maximum efficiency by a long thin column. The minimum resistance is obtained with large granules loosely packed, the maximum efficiency with very small granules lightly packed and so held under pressure. Bracken and Sanderson(1955) showed that sodalime granules in the range size 4-6 offered only two thirds of the resistance of those in the range 6-8. Hunt(1955) found that granules in the range 14-20 offered seven times as much resistance as those in the range 4-8 Robson and Pask(1954) and Hunt showed that the resistance is doubled by tight packing. The shape of the canister can also contribute to the resistance and from the work of Adriani & Byrd (1941) and Adriani(1947) it seems that canisters of many shapes are satisfactory but essentially cylindrical units are to be favoured.

In the experimental work granular size of 8-12 mesh as supplied by the manufacturer were used but it was found necessary for the canister after charging to be agitated to compact the granules. A requirement of BS4667 (1971) is that charged canisters or cartridges should be placed in a tray and arranged so that each has a movement of 6mm. The tray is then subjected to a horizontal reciprocating motion at a

rate of 185-190 cycles/min with a stroke amplitude of 83 mm.

The canister of OX.1 equipment was cylindrical and in the case of OX.2 was eliptical.

3.3.1.2 Open Circuit The total resistance to respiration offered by an open circuit breathing apparatus is stated in Section 1.5 as imposing upon the wearer a physiological burden due to the resistance offered by the demand and exhalation valves. In the bench tests described in Sections 2.2.1 and 2.2.2 these were evaluated under constant flow conditions and indicated that there was an advantage to inhalation resistance if the pressure on the demand valve was constant. No significant variation in the performance of the exhalation valves were apparent as the design characteristics were similar ie an orifice for passage of air and mushroom flap for closure or opening the orifice. BS 4667 (1971) published since the completion of these tests requires a standard of performance of dynamic resistance to breathing to be not greater than 50 mmH_2O for neither the inspiratory nor the expiratory side of the circuit.

3.3.1.3 Comparison of resistance to breathing - Closed and Open Breathing circuits. The comparison of the results obtained from the bench tests are shown in Table 1.3 for a 20 l/min flow.

The closed circuit results were obtained from a sinusoidal flow pattern which was typical of the apparatus in use.

Equipment ref.	Resistance mm H_2O	
	Inhalation	Exhalation
OX.1	25.3	25.3
OX.2	17	30
CA.1	35	12
CA.2	12	8
CA.3	42	12

TABLE 3.1 Exhalation and inhalation resistance at 20 l/min flow

From these results the open circuit apparatus CA.2 fitted with 1st stage reducer would appear to offer the least resistance to a wearer. Table 3.2 shows the effect of increased flow to 80 1/min and again the advantages of the open breathing circuit is shown.

Equipment ref	Resistance mm H_2O	
	Inhalation	Exhalation
OX.1	104.14	104.14
OX.2	52	75
CA.1	68	17
CA.2	20	15
CA.3	62	19

TABLE 3.2 Exhalation and inhalation resistance at 80 1/min flow

3.3.1.4 Summary It is suggested that the most satisfactory type of breathing circuit from the resistance to breathing is the open circuit type with the cylinder pressure reduced at the demand valve to 7 bar.

Standards of allowable resistance for an escape type apparatus are suggested as follows:-

(i) The apparatus should be tested in full working trim by sinusoidal air flow at minute volumes of 20,40,80 and 100 1/min. tidal volumes of 2.1.

(ii) The rate of respiratory resistance expressed as mmH_2O should not be greater than 60 on either the inspiratory or expiratory side of the circuit.

3.4 Condition of respirable gas When considering this aspect of self contained breathing apparatus it is again necessary to examine the two principle types separately as the constituents of the respirable gas are different.

3.4.1 Open circuit apparatus In the apparatus used in the experimental work the air supplied to the wearers was ordinary atmospheric air compressed in a steel cylinder to 193 bar. An important factor was to ensure that the charging of the cylinders was under a controlled condition so that impurities did not contaminate the air being charged. As a full face respirator was being worn with the equipment the question of CO_2 from exhalation build up had to be considered. The temperature of the inhaled air should be constant and presented no subjective discomfort to the wearer.

In all the experiments conducted there were no particular problems associated with any of the equipments from the conditions of respirable gas supplies. The CO_2 content measured in the face mask during and at the end of the experiments was at 5% max. for CA.1 equipment, the temperature rise was only $1^{o}C$. The high concentration of CO_2 was attributable to the position of the demand valve assembly ie on cylinders giving a low pressure in the face mask on inhalation, therefore poor clearance of dead space when compared with CA.2 & 3 equipments where the demand valve assembly was mounted on the face mask.

3.4.2 Closed circuit apparatus The apparatus used in the experimental work posed three problematic areas as far as the respirable gas was concerned. In these equipments the respired air of the wearer is rebreathed after purification ie carbon dioxide being removed and as this action is a chemical one the temperature of the breathing circuit is elevated. The breathing circuit is also dependent on the addition of oxygen sufficient for the respiratory process to be maintained. These aspects are discussed in detail in the following sections.

3.4.2.1 Carbon dioxide content The percentage of carbon dioxide in the inspired air of a closed circuit breathing apparatus is most important because of the effect in increasing the respiratory rate and hence

volume of air breathed. It is therefore necessary to control the level so that no adverse physiological effect results.

Three factors govern the carbon dioxide content of the inspired air: the effective dead space of the circuit, the performance of non-return valves, and the chemical efficiency of the absorbent canister.

Where full face masks are used the dead space is of greater importance. The cavity between the mask and the face depends on the fit and on the facial characteristics of the wearer. Inner masks and ducts can be used to direct the flow of air in the mask and it is claimed that the effective dead space may be reduced to about 65 ml by this means. Griffin and Longson(1971)have reported on this problem and suggested face masks dead space should not be greater than 300 cc for closed circuit apparatus. In the OX.1 and 2 equipments which were designed primarily for purposes of escape a single breathing tube was used and the volume of the circuit between the mouth and the bed of the absorbent was therefore minimised by this design attribute and the dead space volume was at a minimum condusive with the design.

Any efforts to reduce dead space by careful design of face mask and other components can be completely ruined by sluggish valves in the breathing circuit.

The slip of a non-return valve can be defined in terms of the volume of the air passing back through it owing to sluggishness in closing during the reversal of the air flow ie if 2,000 ml passes through a valve during inspiration or expiration and 100 ml passes backward during it's closure the slip is 5%. Clearly the slip, or more strictly the slip plus leakage of the valve in the expiratory circuit is more important than that of the inspiratory valve with regard to rebreathing expired air, the first portion of the expired air contains relatively little carbon dioxide compared with that at the end of expiration.

OX.1 equipment being a pendulum breathing circuit had no valves on the inspiration side of the circuit any return through the relief valve on the breathing bag would be subject to the action of the absorber before inhalation. OX.2 equipment had a non-return valve in the area of the breathing tube connection and initially the CO_2 build up on the circuit was noticeably higher than the OX.1 equipment.

The third and most important factor governing the carbon dioxide content of the inspired air is the chemical efficiency of the absorbent. The design of the canister has been discussed previously and it suggested that this is the major contribution to the problem of resistance of the closed circuit apparatus. It is also a source of the heat generation and it's overall performance has a predominant effect on a wearers comfort. The choice of the absorber lies between caustic alkali and sodalime, the latter being used on the equipments evaluated in the experimental work. In the course of discussion with designers during the visit to Germany as part of this research, cartridges filled under factory conditions using alkali have been adopted for 2 hour and long duration apparatus on the basis that the caustic soda retains some of the water produced in the neutralization therfore the respirable gas is considered more comfortable to breathe. Hartwell and Senneck(1956) and Senneck(1959)have reported fully on the comparison of absorbent materials when used with liquid oxygen breathing apparatus.

During the bench testing of equipments OX.1 and OX.2 the efficiency of the purifying canisters was evaluated under tidal flow conditions of 40 l/min by introducing a 5% carbon dioxide/air mixture saturated at a temperature of 37°C and the CO_2 content of the circuit reached a maximum of 2.1 and 2.0% respectively.

During the inexperienced wearer evaluations the CO_2 content for OX.1 equipment reached a maximum of 2.8% @ a 50 watt constant work rate and 2.5% a work rate increasing at 10 watts/min.

3.4.2.2 Effect of Temperature and Humidity Both the humidity and the temperature of the inspired gas have an important effect on a wearers comfort. With all existing types of compressed oxygen breathing apparatus the problem of high inspired air temperatures usually from fully saturated air has been known for many years. Although the air in the breathing circuit is at ambient temperature initially, see Fig 3.1 page 153 this soon rises in the breathing circuit because

(i) the air expired by the wearer is near body temperature.

(ii) the expired air is cleansed of carbon dioxide by passing through a chemical absorbent giving rise to a reaction which is strongly exothermic.

Several methods have been tried to cool the circulating air before inspiration but the only one favoured is the use of a cooler containing a chemical which changes state from solid to liquid. The coolant being sodium phosphate dodecahydrate which liquifies at 36.1^{o}C with heat of fusion of 66.8 cal/g. The specific heat of the salt is 0.4 cal/g/^{o}C so that the initial warming of the salt to its melting point contributes little to the total cooling. This also imposes a burden on the wearer due to the additional weight to be carried. The difficulties with high temperature and humidity in early compressed oxygen apparatus stimulated the development of types using liquid air. Since the boiling point of liquid nitrogen is -196^{o}C and that of liquid Oxygen -183^{o}C the air entering the circuit in a liquid air apparatus is initially quite cool. However once an apparatus has been worn the exothermic reaction of carbon dioxide absorption begins to counteract the initial low inspired air temperature.

Having considered the above features it is suggested that some future developments of breathing apparatus should be aimed at an average maximum inspired air temperature of 37^{o}C.

Whilst it is not intended to discuss the detail merits of liquid air or oxygen or compressed oxygen, from an operational point of view, it must be stated that of the closed circuit apparatus suitable for escape purposes, only the compressed oxygen type of equipment will be ready for immediate use and it is recognised that it will be more difficult to achieve a temperature of 37°C when using compressed oxygen. The immediate availability of equipment for use is of prime importance and an inspired air temperature of slightly more than 37°C would be acceptable providing the circulating air does not cause heat gain by the wearer. This can be achieved if the inspired air is not fully saturated with water vapour. Over many years attempts have been made to cool the air in compressed oxygen apparatus but without very striking success and perhaps more useful progress could be made by an effective and simple means of drying the inspired air.

The results of the temperature rise in the experimental work with the inexperienced wearers was 18° (a maximum of 41°C) during the constant work rate investigation and 22° (a maximum of 44°C) during the increasing work rate experiments. All the wearers commented on the subjective effect of this, also the misting of the facemask visor was due to the temperature rise and if given an optional choice the wearers would in every case have selected the compressed air open circuit equipment as the preferred equipment from this aspect.

3.4.2.3 Oxygen Content of Inspired Air In establishing the low limit for Oxygen content of the respirable air in a closed circuit breathing apparatus the concentration should never fall below that of ordinary air 21%.

The initial oxygen concentration in the circuit is of course high 98% for OX.1 and 72% for OX.2. There is strong evidence that breathing high oxygen concentrations delays the onset of fatigue. Bannister and Cunninghan(1954)found that subjects were able to run up a gradient at constant speed for between two and three times as long when breathing 66% oxygen as when breathing air before becoming exhausted. Although their results show that there is very little risk of harm from breathing pure oxygen for a limited period while at rest the results of their work suggest that during hard work the cerebral circulation can be increased to such an extent that toxic effects on the central nervous system may be produced over a period. They rely on this possibility to explain the depressing mental effect and the lower physical performance found with breathing 100% oxygen as compared with 66%. Although the evidence appears to be somewhat fragmentary in this area of research it would seen desirable that in a closed circuit apparatus the optimum oxygen concentration might be considered to lie between 60 and 70%.

Fig 3.2 page 153 shows the oxygen concentration for OX.1 and OX.2 apparatus. The initial high concentration for OX.1 equipment is due to using the oxygen flow to purge the breathing circuit. With inexperienced wearers this design attribute offers an advantage and dispenses with the preliminary flushing out process by a wearer prior to using the equipment.

In both equipments the oxygen concentration of the circuits fell to 60% within 5 minutes and this is considered to be physiologically acceptable.

3.5 Effective duration The duration of the equipments used in this study may be defined as "the time for which it functioned satisfactorily". Again the design of the breathing circuit can effect this requirement.

3.5.1 Closed circuit the principle of the design of equipment OX.1 used with the inexperienced subjects in the experimental work was that of a pendulum breathing system this is the simplest and cheapest form of circuit. The wearer breathes to and fro in a single tube through the canister and in and out of the breathing bag, the system was topped up from a 40 litre cylinder of oxygen compressed to 198 bar and the effective duration as claimed by the design manufacturer was 15 minutes.

The results of this aspect as summarised in Table 2.20 show that under a constant work rate of 50 watts the effective duration ranged between 17.9 and 20.8 minutes. In the individual results however duration below these figures was experienced, these were attributed to face seal leakage, this is discussed in detail in Section 3.6.

Under the increasing work rate of 10 watts/min effective duration ranged between 13.3 and 16 minutes. It would appear therefore that this type of breathing circuit with a good fitting face mask could be rated as having an effective duration of 15 minutes.

3.5.2 Open circuit the principle of the type of equipment CA.1 used with the inexperienced subjects in the experimental work was that of a supply of 400 litres of compressed air in a cylinder was fed to a valve operated by the wearers respiratory demand, the air passing through a breathing tube into a full face mask fitted with an exhalation non-return valve the exhaled air passing via this valve to atmosphere. There is no mixing or rebreathing of the exhaled

air. As the air only flows to meet the inspiratory requirements there can be a considerable wastage of available oxygen in the expired air and the consequent limited duration of use due to an unnecessary respiratory cycle. The manufacturer claimed for this equipment an effective duration of 10 minutes.

The results of the evaluation of the duration of this equipment in the experimental work is shown in Table 2.15 show that it ranged from 13.7 to 17.1 minutes with an average duration of 15 minutes related to an averaged minute volume of 24.4 l/min for a 50 watt constant work rate. With an increasing work rate @ 10 watts/min the effective duration ranged between 11.5 and 16.7 minutes with an average duration of 14.2 minutes related to an average minute volume of 29.4 l/min. The peak minute volume experienced during the increasing work rate was 51 l/min at the end of the exercise the minute volume at the start for this subject being 16 l/ min, the average 30.5 l/min. In the 48 to 58 years age Group 4 subjects an average minute volume of 39 l/min was however experienced for one wearer.

3.5.3 Summary From the experimental work conducted it is suggested that a closed breathing circuit based on the design of the OX.1 equipment could be rated as having an effected duration of 15 minutes.

The escape duration of open circuit apparatus should be defined as the period of time in minutes arrived at by dividing the fully charged capacity of the cylinder in litres by 40 ie assuming an air flow rate of 40 litres a minute as a minimum for the apparatus.

3.6 Face mask inward leakage In the experimental work described in Section 2.7 the purpose was to investigate the inward leakage rate through a number of peripheral facial seal designs of full face respirator masks, using a dynamic method of test. This method

determined the leakage of the external atmosphere into the face mask of the order of 0.001% accuracy while the subjects performed various exercises.

The inward leakage rate of each type of mask was determined for six clean shaven subjects and the results are shown in Table 2.25. The 4 masks tested had been supplied as being suitable for use with self contained breathing apparatus and were of moulded rubber material with the following racial seal designs.

CA.1 (Fig 1.6) Air cushion

CA.2 (Fig 1.7) Inflated pneumatic

CA.3 (Fig 1.8) Foam plastic fitted

OX.1 (Fig 1.9) Plain

The method of head suspension was elasticated in the case of CA.1 and OX.1 and self adjustable in respect of the CA.2 and CA.3 masks. The subjects participating in these investigations were all trained in experimental physiological investigations and fitted the face masks themselves and checked for gross leakage by closing the breathing tube and trying to inhale. When leakage was apparent the masks were re-adjusted.

It was noted that the manner in which a given force is addressed to the face would be relative to the design of seal and the subjective assessment of the wearer on comfort.

This however was not taken in consideration in the investigations as experienced wearers participated. Burgess and Hinds(1970)have reported on this subject for three facial seal designs utilising a psycho-physical technique and galvanic skin potential as a measure of discomfort.

From the results shown in Table 2.25 it can be seen that inward leakage occurred from 0.005 to 0.041% or 46 to 413 ppm. Since it appears that all face masks leak, care must be taken in the choice

of the face mask design. When face masks are worn in some less toxic atmospheres a amount of leakage may be acceptable but particular care must be exercised before certain face masks are used in highly toxic atmospheres.

Considering the results obtained from the investigations of inward leakage it is necessary to relate these to an assessment of the rates of leakage in terms of a wearers exposure to known contaminants in an irrespirable atmosphere. The possible toxic effects will vary with the contaminants, their concentration and the length of exposure. Carbon monoxide has been a toxicological problem to man throughout his history. The problem began when man encountered his first fire and has continued to increase in significance to the present time quite apart from naturally occurring carbon monoxide is swamps and other geographical locations. Carbonmonoxide is currently the most important gaseous poison found in industry. Table 1.4 shows that in the last decade 737 incidents were reported to the Factory inspectorate of carbonmonoxide gassing accidents of these 59 were fatal.

In respect of wearers of breathing apparatus inward leakage carbon monoxide being odourless is consequently more hazardous than gases with distinctive smells.

It is also difficult to be specific about the concentrations of carbonmonoxide which are likely to be encountered as a result of a fire, but trials conducted by the Joint Fire Research Office suggest that a concentration of about 10% is likely to be the maximum except under all but exceptional conditions Skelcher(1965)postulated the situation of CO_2/CO hazard in a nuclear reactor building if the gas circuit was breached.

The Safety in Mines Research Establishment also use 10% as a maximum concentration for carbonmonoxide build-up in mines. The Threshold Limit Value (TLV) for a normal working day exposure to carbon monoxide has been set by the Department of Employment at 50 ppm the effect of exposure for 1 hour to a concentration of 200 ppm (4 times TLV) has been indicated in Table 1.1 as giving headaches and throbbing in the temples, Shulte(1963)related this in terms of 20-30% COHb and the investigations of other researchers have indicated that concentrations of carbonmonoxide in the blood in excess of 25% showed changes in physiological activities.

For the purpose of this discussion a figure of 200 ppm has therefore been selected as the maximum concentration of CO which could be expected to be tolerated by inward leakage by wearers of self contained breathing apparatus without undue physiological effects.

On the basis of this statement the following would be the results of various permissible inward leakage.

In 100%	concentrations	of	CO	the	acceptable leakage	would be 200 ppm
In 50%	"	"	"	"	"	" 400 ppm
In 20%	"	"	"	"	"	" 1,000 ppm
In 10%	"	"	"	"	"	" 2,000 ppm
In 5%	"	"	"	"	"	" 4,000 ppm

From these figures it can be established that all the face masks tested would be acceptable in irrespirable atmospheres containing a 50% concentration of carbon monoxide. Masks which only just comply with the British Standard requirement would however fall short of this concentration as the requirement has been set at 500 ppm.

If however the irrespirable atmosphere contained a more toxic substance say chlorine where the threshhold limit value for an 8 hour exposure

is set at 1 ppm and on the previous assumption that a figure of 4 times the TLV is acceptable and in this case as shown in Table 1.3 the resultant symptoms being slight smarting of the eyes and irritation of the nose and throat, the acceptable leakage rates would be:-

In	100%	concentration	of	chlorine	the	acceptable	leakage	would be 4 ppm
In	50%	"	"	"	"	"	"	" 8 ppm
In	20%	"	"	"	"	"	"	" 20 ppm
In	10%	"	"	"	"	"	"	" 40 ppm
In	5%	"	"	"	"	"	"	" 80 ppm

Under these conditions none of the masks evaluated would be acceptable for conditions where the concentration of chlorine in the atmosphere exceeded 5%.

It is considered necessary to record that most chlorine water treatment plants used in industry are installed in confined buildings and it is suggested that under such conditions, in the event of an incident of plant failure resulting in a leakage of chlorine into the atmosphere the concentration found within the building would be in excess of a 5% concentration stated above.

3.6.1 Effect of Facial hair

Griffin and Longson(1972)have reported as shown in Table 3.3 that facial hair when present between the face and face mask seal also presents an inward leakage problem and demonstrated the superiority of the pneumatic seal face mask in such cases.

	Plain seal	Pneumatic seal
Full beard	5.130 ppm	2.970 ppm
Sideburns only	3.020 ppm	235 ppm
Clean shaven	720 ppm	45 ppm

TABLE 3.3 Summary of face mask leakage results in ppm six subjects wearing plain and pneumatic seal face masks.

Carter and Heaton(1972)have also reported rather inconclusively,into the effects of wearers with full beards and sideburns on the fit of face masks. The atmosphere used in all tests was from smoke generators and the leakage was subjective assessment by the wearers.

3.6.2 Face mask Outward Leakage Since inward leakage occurred in all the face masks examined outward leakage will therefore occur when there is a positive pressure in the face mask and in the observed results shown in Tables 19 to 22 indicate this effect when face mask OX.1 was used with a closed circuit breathing apparatus.

In this equipment a supply of oxygen under high pressure was introduced into a closed breathing circuit, the outward leakage from the face mask seal in this case plain rubber may be sufficient to create a flammability hazard to the wearer. Denison and Tomkins(1967) have reported that the outward leakage of oxygen from some oral nasal mask design may be sufficient to create a flammability hazard.

In general the pressures in a mask are determined by the design of the breathing circuit and in particular the action of the relief valve. With an automatic relief valve the pressure in the mask depends largely on the opening pressure of the valve. With a manually operated relief valve the position is rather more complicated since the use that the

wearer makes of the relief valve depends on his subjective response to breathing.

In OX.1 equipment Fig 1.12 page 64 an automatic relief valve is fitted and the operation of which depends solely on the pressure in the mask and breathing bag.

In OX.2 equipment Fig 1.14 page 66 the relief valve is manually operated and depends on the wearers subjective response to the breathing resistance of the circuit.

Griffin and Longson(1971)conducted a series of experiments to examine the ignition hazard associated with face mask outward leakage and stated that when the pressure in masks was less than 12 cmH_2O the leakage was probably harmless but wearers also experienced difficulty in breathing out above this figure, and became aware of the need to operate their relief valve.

3.6.3 Summary This stage of the work confirms the need for care in the choice of full face masks, the importance of correctly fitting the face mask to the wearer and the advisability of using breathing apparatus with well designed automatic relief valves.

3.7 Positive pressure device to minimise inward leakage

A possible solution to the problem of in-ward leakage on open circuit breathing apparatus appeared to be, as a result of this research to introduce a method of a positive pressure seal between the wearers face and seal of the face mask.

Such a device is shown in Figure 3.3 page 154 where demand valve assembly CA.2 Figure 1.3 page 55 has been modified to allow a wearer to manually operate a switch to bypass the demand valve flow and introduce into the face mask a continuous flow of air to pressurise the face mask.

This device will prevent the inward leakage of the atmosphere into the mask. The disadvantage is that the exhalation resistance of the valve has to be increased to maintain the pressure seal. This is considered physiologically acceptable and the comparison of this increase with exhalation valve resistance without the device is shown in Table 3.4

Flow	l/min	20	50	80	140	150	160	170
Standard Exhale	mmH_2O	5	10	12.5	30	32.5	35	37.5
Duaflow Exhale	mmH_2O	52.5	55	62.5	80	82.5	87.5	90

TABLE 3.4 Comparison of Exhalation Resistance with Standard and Duaflow Demand Valves

A further disadvantage is that if the wearer has abnormal facial characteristics resulting in a continuous flow from the face mask the effective duration of the equipment will be shortened. This has not yet been accurately determined but it is estimated that a fall short by 10% of the effective duration would be expected with extreme cases of awkward facial characteristics.

This aspect should be investigated further.

3.8 Wearer Comfort The subjective assessment of the inexperienced subjects to comfort in the assessment of OX.1 and CA.1 equipments was that the open circuit compressed air apparatus was the first choice of all subjects. The high inspired gas temperatures of the OX.1 equipment was assessed as intolerable by the majority of wearers and this was emphasised by the fact that 5 of the sample group declined to undertake the increasing work rate experiment.

The CA.1 equipment also had the advantage that it was entirely automatic in use, this being accomplished by using the demand valve

assembly in place of the conventional cylinder valve. When the wearer placed the mask to his face and inhaled the apparatus functioned.

OX.1 equipment required the wearer to operate a cylinder valve after donning the face mask and some wearers tended to show concern if the valve was not opening easily. The design principle of the flow control unit of this apparatus is however to be commended as the initial purging of the circuit by the initial high flow eliminated the wearer from purging the breathing circuit before opening the cylinder valve.

3.9 Conclusion This study has been associated with the evaluation of self contained breathing apparatus designed to enable an inexperienced wearer of this type of equipment to escape from a work area which is irrespirable normally due to the presence of dangerous gases or vapours, both physiological aspects and engineering performance have been considered.

3.9.1 Definitions For the purpose of this work the following definitions have applied.

(i) Escape breathing apparatus - A simple short duration apparatus used for escape purposes only which will enable a wearer to breathe independently of the immediate atmosphere.

(ii) Self contained breathing apparatus - An apparatus using a single supply of respirable gas from a cylinder which is an integral part of the apparatus there being two suitable types.

(a) Open circuit escape breathing apparatus - Apparatus in which compressed air carried in a cylinder is fed through a demand valve and breathing tube to a full face mask and exhaled air passes through a non-return valve mounted on the face mask to atmosphere.

(b) Closed circuit escape breathing apparatus - An apparatus designed so that the exhaled air of the wearer passes from a full face mask through a breathing tube into a purifier containing chemicals which absorb the exhaled carbon dioxide. Oxygen being fed into the breathing circuit from a cylinder of compressed oxygen forming part of the apparatus. The oxygen and purified gases mixing in a breathing bag the wearer inhaling from this bag. Any excess gas being released from a non-return valve fitted to the breathing bag.

Escape duration The escape duration of the apparatus is the time in minutes for which it can be expected to function satisfactorily.

3.10 Suggested standards of performance Following the experimental work and methods described in Chapter 2 some of the requirements of a specification for short duration breathing apparatus are now suggested.

3.10.1 Resistance to breathing (i) Closed circuit apparatus. Neither the inspiratory or the expiratory side of the circuit shall have a dynamic resistance greater than 60mmH_2O when tested in accordance with the method described in Section 2.1.1 and summarised as follows:-

3.10.1.1 Summary of Laboratory Performance Test

Test Equipment

A breathing machine designed to provide sinusoidal air flows and operating at a rate corresponding to 20 ventilations per minute is required.

Test procedure

The machine is set to deliver to the complete apparatus under test a tidal volume of 2 litres of a 5% (by volume) carbon dioxide/air

mixture at a temperature of 37°C and fully saturated, the total delivery being 40 litres per minute. The test is run continuously for a period equal to the effective duration of the apparatus.

In a separate test the sinusoidal air flow increased to 80 then to 100 litres per minute for a period sufficient for an assessment to be made of the functioning of the apparatus at this flow rate.

If the material used for absorbing carbon dioxide is contained in a canister or cartridge, the laboratory test is made on the apparatus after the purifier has been subjected for 3 minutes to simulated rough usage as follows:

The canisters or cartridges are placed in a tray and arranged so that each has a movement of 6 mm. The tray is then subjected to a horizontal reciprocating motion at a rate between 185 cycles and 190 cycles per minute with a stroke amplitude of 83 mm.

(ii) Open circuit apparatus. The resistance of the inspiratory circuit shall have a dynamic resistance greater than 60mmH_2O and the expiratory side of the circuit of not greater than 25mmH_2O when tested in accordance with the methods described in Sections 2.2.1 and 2.2.2 respectively.

3.10.1.2 Practical performance test. The apparatus should be subjected to a practical performance test as described in Section 2.6 and summarised below to assess

(i) Condition of inhaled air for

(a) Oxygen content when closed circuit apparatus is being assessed should not fall below 21% (by volume).

(b) Carbon dioxide content should be of the inhaled air excluding dead space effects should not exceed 2.0% (by volume).

(c) Temperature of the inhaled air measured at a position as near to the breathing zone as possible shall not exceed 40°C during the effected duration of the apparatus.

(ii) Effective duration to assess in minutes the time of which the apparatus functioned satisfactorily.

(iii) Comfort. When tested in accordance with the procedure the apparatus shall be such that it is worn without avoidable discomfort and with little impediment to movement.

Summary of Test procedure for Practical Performance test.

The breathing apparatus should be tested by 5 subjects who must be experienced in the use of breathing apparatus.

The subjects wearing the apparatus pedal a cycle ergometer set at 50 watt constant work rate.

Each test is continuous without removal of the apparatus for the full period of the effective duration of the apparatus.

Measurements being taken of oxygen, carbon dioxide of the inspired gas together with the temperature of the inhaled air at the start and completion of the test.

3.10.2 Face mask Performance Face masks shall cover the eyes, nose, mouth and chin and shall provide adequate sealing on the face of the wearer of the equipment against the outside atmosphere when the skin is dry or moist when the head is moved and when the wearer is speaking.

The fit of the face mask against the contours of the face shall be such that when tested in accordance with the method described in Section 2.7 and summarised below the inward leakage of the test contaminant between the face mask and the wearers face shall not exceed a value of 0.02%.

Face masks shall be secured to the face by means of an elasticated harness light in weight and comfortable to wear the weight shall be symmetrically balanced to ensure the maximum retention of the face seal and to minimise muscular strain.

Face masks shall have suitable visors complying with the optical quality of BS2092.

3.10.2.1 Summary of Test procedure for inward leakage of facepieces

Test subjects Ten clean shaven persons are selected, covering a broad spectrum of facial characteristics(excluding significant abnormalities). It is to be expected that, exceptionally, some persons cannot be satisfactorily fitted with a full facepiece; such exceptional subjects should not be used for testing facepieces.

Facepieces. If more than one size of facepiece is manufactured, the test subjects are supplied with the appropriate size and at least three facepieces of any one size are tested.

Test procedure. Each test subject wearing the facepiece under test complete with breathing tubes, is enclosed in a plastic hood which is loosely tied around his waist and around the breathing tubes so that leakage is minimised. The inside of the hood is maintained at a pressure not more than 3mmH_2O above atmospheric by supplying pure argon to the interior of the hood. (By preliminary inflation of the hood with argon and then by adjusting the argon supply when the hood has been fitted, the atmosphere surrounding the facepiece is maintained at the concentration obtained from the argon cylinder).

Each subject walks on a treadmill at 6.5 km/h whilst separately carrying out various head movements and reciting the alphabet.

The subject inhales through a breathing tube from a lung-governed oxygen supply and exhales through a breathing tube and a sampling bladder to atmosphere. The amount of argon in the expired gas is determined eg using a mass spectrometer, and compared with the argon present within the hood to obtain the faceseal inward leakage expressed in ppm.

3.10.3 Relief Valve Breathing apparatus of the closed circuit type shall be provided with a relief valve operated automatically by the pressure in the breathing circuit and designed so that the external atmosphere cannot enter the apparatus during use. The relief valve which shall include an additional non return valve, shall be protected against dirt and mechanical damage. Means shall be provided for sealing the relief valve to permit leak testing.

The relief valve shall have the following performance characteristics:-

(a) The opening pressure of the moist relief valve measured at a constant flow rate of one litre/min shall be between 15 to 40 mm H_2O in any position.

(b) The resistance of the relief valve to an air flow of 50 l/min shall not exceed 70 mmH_2O in any position of the valve.

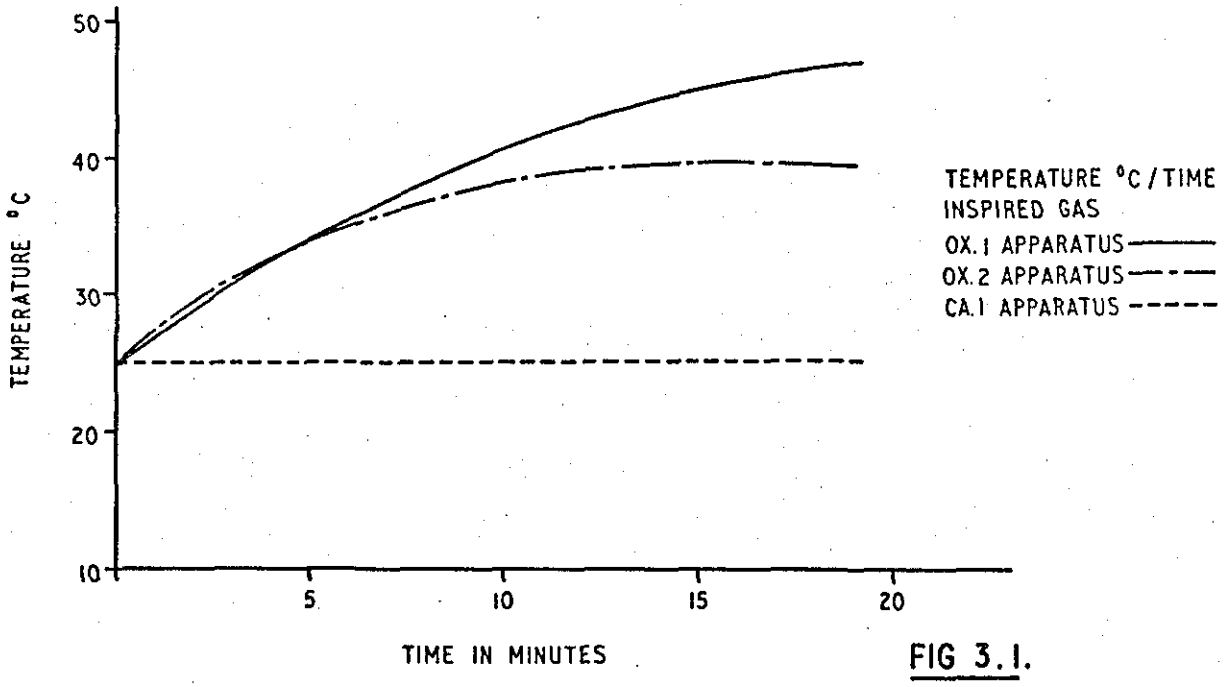

TEMPERATURE °C
50
40
30
20
10
5
10
15
20
TIME IN MINUTES
TEMPERATURE °C / TIME
INSPIRED GAS
OX.1 APPARATUS
OX.2 APPARATUS
CA.1 APPARATUS

FIG 3.1.

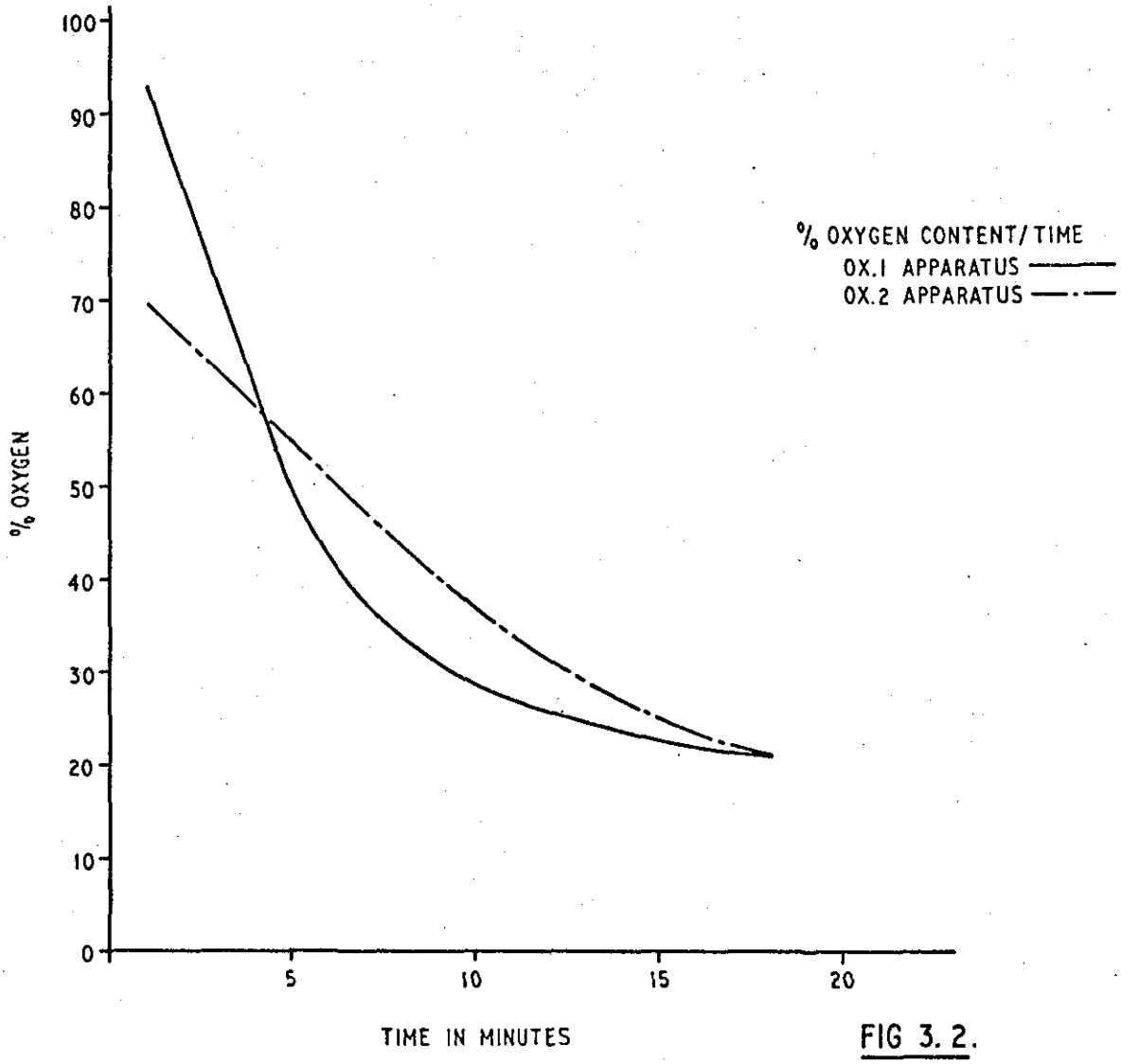
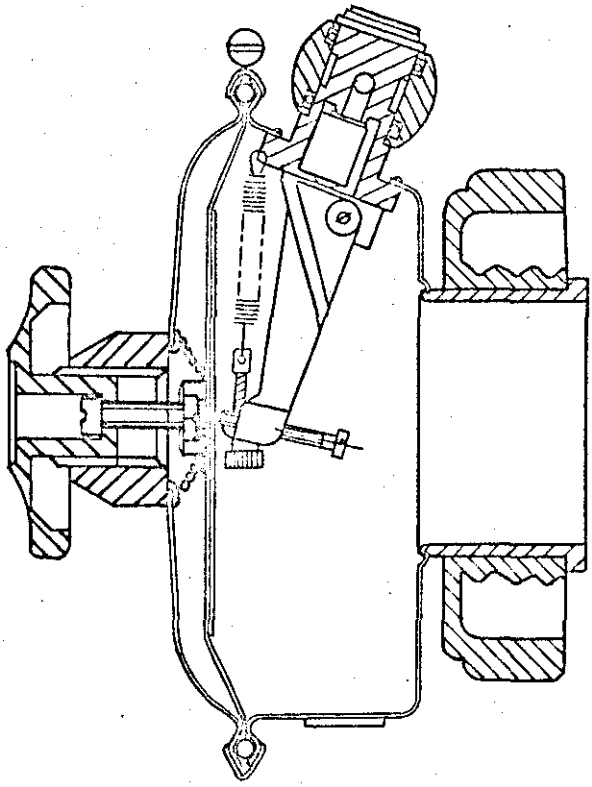
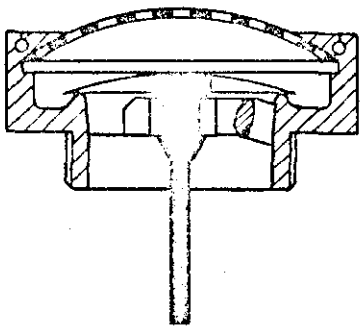

% OXYGEN
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
TIME IN MINUTES
% OXYGEN CONTENT/ TIME
OX.1 APPARATUS
OX.2 APPARATUS

FIG 3.2.



DEMAND VALVE



EXHALATION VALVE

C.E.G.B	S.E. REGION
MODIFIED CA.2. DEMAND VALVE ASSEMBLY FOR POSITIVE PRESSURE FLOW	

1st. ISSUE	A		FIG. 3. 3.	SER 632/11
10. 7. 72.				

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