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SELECTION OF A GAS AND FLOW RATE FOR THE BAILOUT ASSEMBLY USED IN THE CANADIAN CLEARANCE DIVING APPARATUS

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1.0 INTRODUCTION

1.1 Background

1.1.1 The Canadian Clearance Diving Apparatus (CCDA), Figure 1, is a closed/semi-closed circuit re-breather apparatus. It comprises two sub-systems, *i.e.*, a breathing loop and a gas supply system. The breathing loop consists of a carbon dioxide (CO_2) scrubber, a chest-mounted counterlung, breathing hoses and a full facemask (FFM). The gas supply system, mounted on a backpack, compensates for metabolic oxygen (O_2) consumption by providing the breathing loop with a constant mass flow of either an oxygen/nitrogen (O_2/N_2) gas mixture or 100% O_2. A technical description of the apparatus and its development up to 1988 is given in a report by Marshall and Eaton [1]. Chapple [2] details modifications to CCDA between 1988 and 1992. Further technical information can be found in the CCDA manuals [3,4].

1.1.2 For emergency purposes, the early CCDA [1,2] used a reserve or J-valve on the gas supply manifold, Figure 1, to retain gas in one of the spherical flasks. In the event that

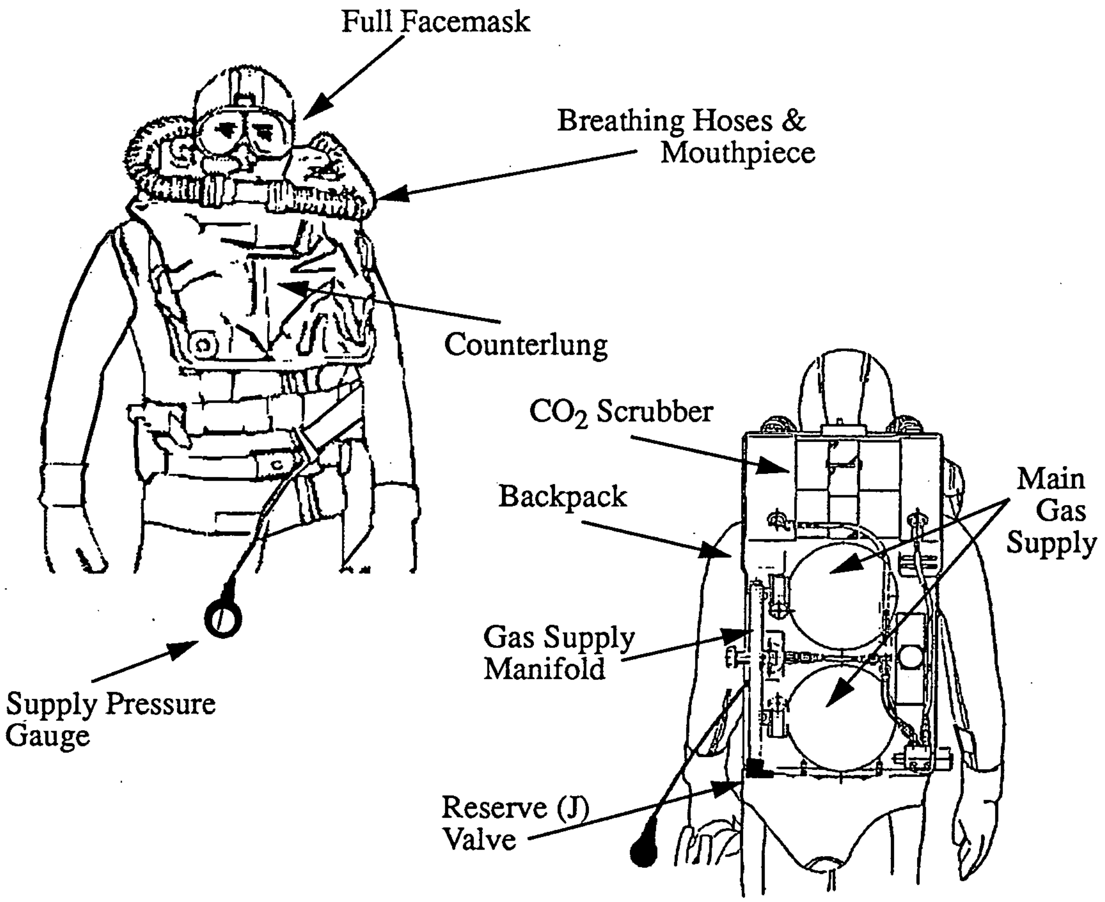

Figure 1. CCDA general configuration prior to the addition of a separate Bailout Gas Supply for emergency situations.

the main supply of gas exhausted before the planned duration of the dive, the diver could actuate the reserve and would have approximately 10 minutes to return to the surface. However, if the diver did not notice the loss in pressure (by observing the flask pressure gauge), the J-valve would allow gas to flow until only about 5 minutes of gas remained in reserve. Canadian Forces (CF) Clearance Divers considered this an operational problem. The CF decided that a separate gas supply should be used for emergency bailout and recommended the removal of the CCDA J-valve and the use of the Bailout Assembly available with the Canadian Underwater Minecountermeasures Apparatus (CUMA) [5].

1.1.3 However, the CUMA Bailout Assembly uses an O_2/helium mixture unsuitable for CCDA use. Consequently, an appropriate O_2/N_2 mixture and flow rate was needed for CCDA. This report documents the process of identifying the composition and flow of the CCDA bailout gas.

1.2 Equipment Restrictions

1.2.1 National Defence Headquarters/Director of Diving Safety specified that the CCDA Bailout must use in-service equipment *(i.e.*, CUMA Bailout, standard NATO diving gasses) and incur no additional capital expenditure. It was preferred that a single gas would be chosen to suit the entire depth range of CCDA diving, 0 to 54 metres (m).

1.2.2 The CUMA and now CCDA Bailout Assembly, Figure 2, stores gas in an aluminum cylinder (Luxfer, 0.75 litre (L) floodable volume, 205 Bar working pressure) contained in a nylon harness and secured to the body harness below the counterlung. Gas flow is controlled by a post valve, an absolute pressure regulator and a fixed diameter, flowmetering orifice fitted to an output port of the regulator. A braided, brass-jacketed, Teflon® core hose leads to the left shoulder lobe of the counterlung. The Bailout is operated by turning the post valve counter-clockwise.

1.2.3 The standard NATO diving gasses available for use were:

a. 100% O_2;

b. 60%/40% O_2/N_2;

c. 40%/60% O_2/N_2; and

d. 32.5%/67.5% O_2/N_2.

2.0 METHOD

2.1 Mathematical Model Development

2.1.1 With the criteria on equipment and cost set, the problem was reduced to selection of a standard CCDA Bailout flow rate and gas from the NATO gasses. The approach taken was to mathematically model the gas flow balance in the CCDA breathing loop and produce a computer simulation that would allow investigation of different emergency sce-

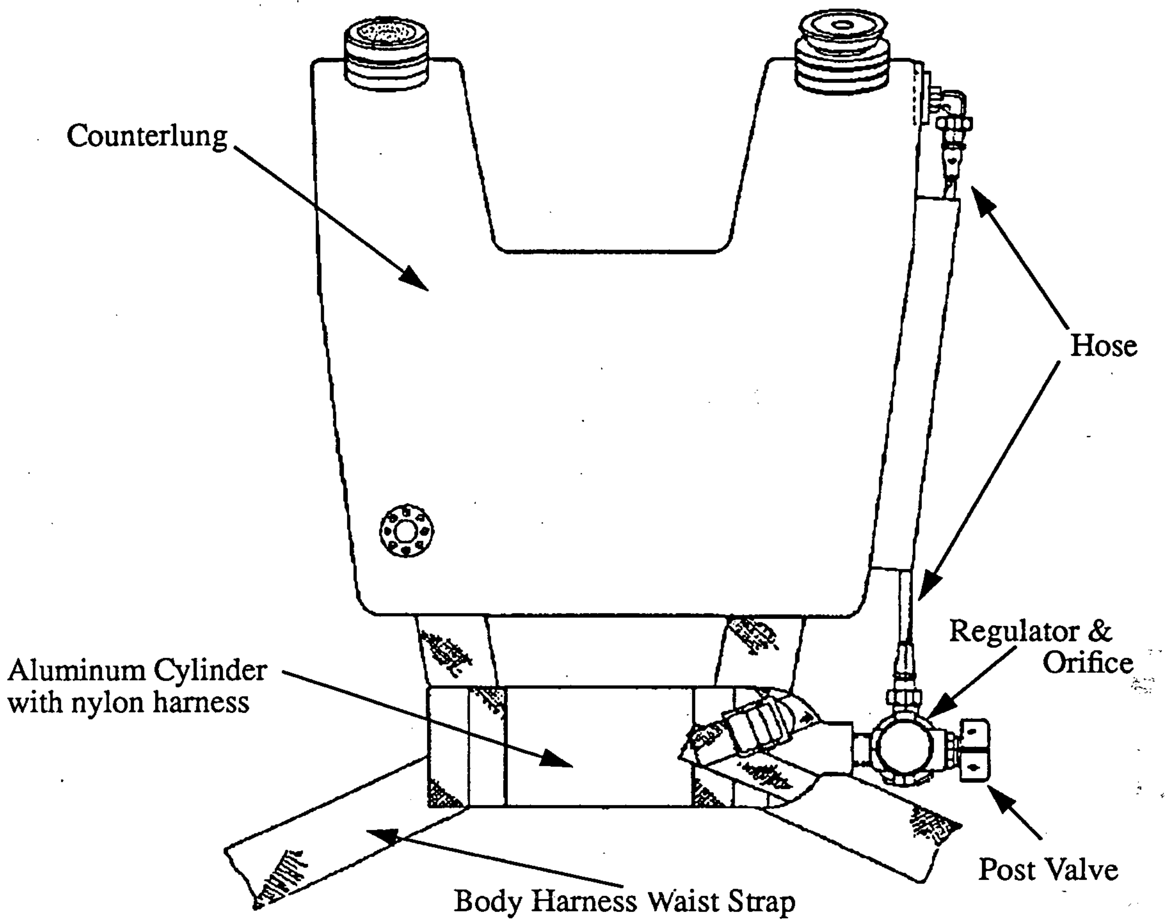

Figure 2. CCDA Bailout cylinder fitted below counterlung with hose attachment to left lobe of counterlung. Opening the cylinder valve allows the gas to flow through a regulator, a flow-metering orifice and finally into the counterlung via the hose.

narios and the resulting breathing mixture available to the diver. The principal variable of investigation was the level of O_2, specifically the O_2 partial pressure (PO_2), breathed by the diver. The PO_2 in the breathing gas is critical to the diver's well-being. Hyperoxic PO_2 levels can cause central nervous system toxicity and convulsive seizures while hypoxic levels can result in unconsciousness. Consequently, the Bailout gas O_2 concentration and flow rate must maintain the PO_2 within safe limits while at the same time provide a reasonable endurance from the available supply.

2.1.2 The PO_2 has an upper and lower safety limit. When considering hypoxic (lack of oxygen) and hyperoxic (oxygen poisoning) conditions, a review of literature [6,7,8,9] suggested PO_2 limits no lower than 0.16 atmospheres, absolute (ATA) and no higher than 2.5 ATA. It was decided that when considering an emergency/short term situation these limits could be used as the diver would not be breathing the Bailout gas for longer than 15 minutes.

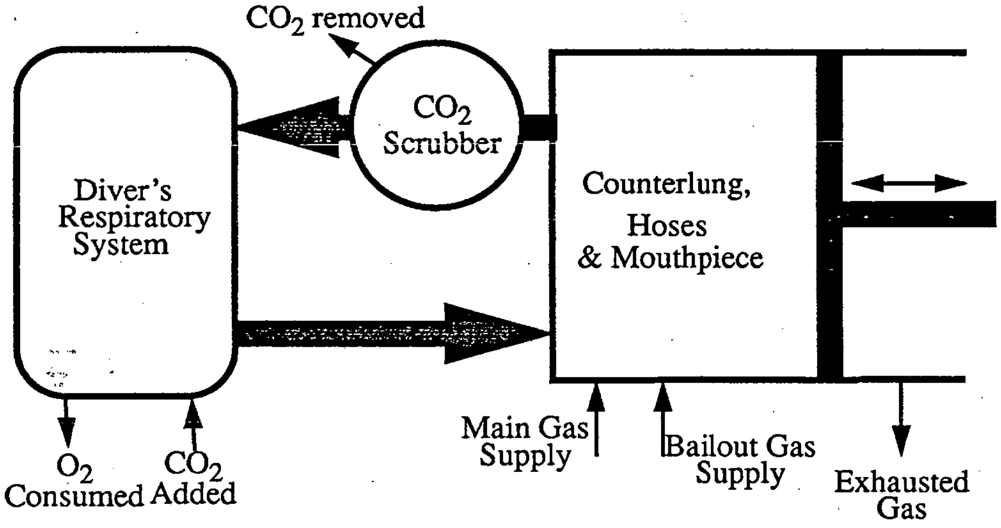

Figure 3. Gas flow diagram for CCDA. The counterlung was modelled as a floating piston to account for counterlung expansion and contraction. Exhaust flow starts when the counterlung volume reaches the limit set by the Buoyancy Control Valve setting.

2.1.3 To determine if PO_2 remains within the safe range the basic relationship is

$$PO_2 = \frac{V_{O_2}}{V_{total}} \times D$$

where V_{total} is the combined volume of the CCDA counterlung and the diver's respiratory system, V_{O_2} is the volume of oxygen in V_{total}, and D is the depth in ATA. This traditional equation assumes steady-state conditions and does not allow for the transient effects of depth changes and the inertia of the gas volumes which slow the change of gas concentrations as gas flow rates and mixtures change. To investigate short term (10 to 15 minute) gas concentrations and pressures in the breathing loop a dynamic model is needed.

2.1.4 The flow of gases between the CCDA breathing loop and the diver, Figure 3, are needed to model the volumes during an emergency scenario. The system is modelled to include the CCDA volumes as well as the volume of the diver's respiratory system. The capacity for the volume to expand and contract was modelled by a floating piston that also opens and closes the exhaust gas flow when the counterlung expands to its maximum volume. The diver was assumed to control lung volumes so that there was no net change of respiratory system volume. Changes in system volume result from the balance of the gasses flowing into and out of the system and from changes in depth.

2.1.5 The O_2 and total volumes can be obtained by integrating, over time, the difference between the sums of flows into and out of the system, so that

$$PO_2 = \frac{\int(\Sigma_{in}Q_{O_2} - \Sigma_{out}Q_{O_2})\,dt + {}_0V_{O_2}}{\int(\Sigma_{in}Q - \Sigma_{out}Q)\,dt + {}_0V_{total}} \times \left(\int D\,dt + {}_0D\right)$$

where Q_{O_2} represents oxygen flow, Q is the combined flow of all gasses, the initial subscript "in" designates gas flowing into the system, "out" designates gas flowing out and "0" indicates the value at the beginning of the integration period. In this study, integration begins when the Bailout is activated.

The sum of the oxygen flowing into the system

$$\Sigma_{in}Q_{O_2} = f_{bail}Q_{bail} + f_{main}Q_{main} + \Delta V_{O_2}^{Boyle}$$

where f_{bail} is the fraction of oxygen in the gas flowing from the bailout supply, f_{main} is the fraction of oxygen in the gas flowing from the main gas supply and $\Delta V_{O_2}^{Boyle}$ is the change in O_2 volume caused by any depth change (referring to Boyle's Law).

2.1.6 The sum of the oxygen flowing out of the system

$$\Sigma_{out}Q_{O_2} = \dot{V}_{O_2} + f_{cl}Q_{ex}$$

where $\dot{V}_{O_2}$ is the oxygen consumed by the diver for metabolic needs, f_{cl} is the fraction of oxygen in the counterlung and Q_{ex} is the exhaust gas leaving the breathing loop via the Buoyancy Control Valve, Counterlung Relief Valve and around the seal of the FFM. (Note: The majority of gas leaving the breathing loop will be through the Buoyancy Control Valve. While ascending the Counterlung Relief Valve may open to exhaust excess pressure in the counterlung. Proper operation of the apparatus minimizes the gas lost via the FFM.)

2.1.7 The sum of all the gasses flowing into the system

$$\Sigma_{in}Q = Q_{bail} + Q_{main} + \Delta V_{total}^{Boyle} + \dot{V}_{CO_2}$$

where ΔV_{total}^{Boyle} is the change in the system volume produced by a depth change and $\dot{V}_{CO_2}$ is the rate of metabolic carbon dioxide production by the diver.

2.1.8 The sum of all the gasses flowing out of the system

$$\Sigma_{out}Q = \dot{V}_{O_2} + Q_{ex} + \dot{V}_{CO_2}^{Scrubber}$$

where $\dot{V}_{CO_2}^{Scrubber}$ is the rate of carbon dioxide removal by the scrubber.

2.1.9 All of the variables in these relationships, except exhaust flow, Q_{ex}, depth related volume changes, ΔV^{Boyle}, and the fraction of O_2 in the counterlung, f_{cl}, were considered independent and therefore needed to be specified. However, the exhaust flow, depth related volume changes and counterlung O_2 fraction could be expressed in terms of the independent variables.

2.1.10 The exhaust flow is zero if the system volume has not reached a maximum. Once the counterlung fully expands, the gas exhausted was calculated as the amount in excess of the maximum volume. In the simulation algorithm, changes in volume produced by depth, *i.e.*, ΔV_{total}^{Boyle} and $\Delta V_{O_2}^{Boyle}$, were determined by correcting the volume at each time increment using Boyle's Law so that $V_t = V_{t-\Delta t} \cdot D_t / D_{t-\Delta t}$, where t is the present time and $t - \Delta t$ is the time at the previous interval. The f_{cl} is a factor of PO_2 and equals V_{O_2}/V_{total}.

2.2 Definition of the Simulation Environment

2.2.1 To specify values for the independent variables, emergency scenarios were developed to estimate reasonable worst case conditions. The scenarios were developed through consultations with CF Clearance Divers. Two basic scenarios were devised, one for hyperoxic conditions the other for hypoxic conditions.

2.2.2 In the hyperoxic scenario the diver's PO_2 starts high at 2 ATA when the Bail-out was activated. The $\dot{V}_{O_2}$ was low, 0.5 litres per minute at 0°C, 1ATA, dry ($L \cdot min^{-1}$ (STPD)) [7], and there was a delay on the bottom of 2 minutes before commencing the ascent. The ascent rate was a slow 9 metres per minute ($m \cdot min^{-1}$). All of these factors would tend to increase PO_2.

2.2.3 For the hypoxic scenario the diver's PO_2 at the time of operating the Bailout was set to 0.5 ATA and the $\dot{V}_{O_2}$ was 2.0 $L \cdot min^{-1}$ (STPD) [7]. The diver left the bottom immediately upon activating the bailout at a high rate of 36 $m \cdot min^{-1}$. The effect was to reduce O_2 levels.

2.2.4 The scenarios examined the condition where the main supply gas flow had failed, *i.e.*, $Q_{main} = 0$. However, it was reasonable to consider that the Bailout could be activated while gas still flowed from the main supply. Consequently, the conditions of the hyperoxic and hypoxic scenario were also used to examine the situation where $Q_{main} \neq 0$.

2.2.5 To reduce the complexity of the simulation $\dot{V}_{CO_2}$ and $\dot{V}_{CO_2}^{Scrubber}$ were assumed equal and removal of CO_2 was considered coincident with its production. Therefore, the volumes and flow rates of CO_2 were eliminated from the model.

2.2.6 The maximum system volume was set at 16 L. The system volume at the time that the Bailout was activated was set at 13 L. This 3 L reduction in the counterlung volume is accomplished by reducing the back-pressure setting on the Buoyancy Control Valve. It is standard operating procedure for divers to partially open the valve to minimize buoyancy and reduce hydrostatic loading on the respiratory system.

2.2.7 A further simplification to the problem arose from the discovery that the flow rate of the bailout gas is restricted by variables other than PO_2. The flow rate associated with each NATO gas mixture normally changes; however, the gas supply available in the Bailout supply cylinder is limited and endurance of the supply becomes a critical parameter. CF Clearance Divers specified a minimum endurance of 12 minutes. It was estimated that the usable volume of Bailout gas was 126 litres (L). Therefore, Q_{bail} was restricted to a maximum of 10.5 $L \cdot min^{-1}(STPD)$. Lower values were not considered as this would increase the amount of time required to inflate the counterlung which would restrict the diver's available breathing volume. Consequently, the problem was reduced to identifying which of the four NATO O_2/N_2 mixtures was suitable.

2.2.8 Table 1 summarizes the values for variables used in the computer simulation for each scenario to determine the safest of the four NATO gasses. Each gas was tested under 12 scenarios.

2.3 Computer Simulation

2.3.1 The computer simulation performed a numerical integration of the time dependent flows and depth. The algorithm was implemented using spreadsheet software (Microsoft Excel, Version 4.0). The time step for all simulations was 1 second. At each step, the volumes were calculated and the total volume was calculated as if there were no restriction on its size. If the system volume was greater than the maximum volume, the volume lost to the exhaust was set to the excess volume and the system volume was corrected to the maximum volume. Simulations ended when the diver reached the surface.

2.3.2 The results of each simulation run were analysed for maximum and minimum PO_2 values. They were also examined to ensure that the volume of gas available in the counterlung was sufficient for breathing.

Scenario	Initial PO_2 (ATA)	Initial System Volume (L)	Maximum System Volume (L)	Initial Depth (m)	$\dot{V}_{O_2}$ $\begin{pmatrix} \mathrm{L \cdot min^{-1}} \\ \mathrm{(STPD)} \end{pmatrix}$	Pre-Ascent Delay (min)	Ascent Rate $(\mathrm{m \cdot min^{-1}})$	Main Gas Supply Flow Rate $\begin{pmatrix} \mathrm{L \cdot min^{-1}} \\ \mathrm{(STPD)} \end{pmatrix}$
Hyperoxic with no main gas flow.	2.0	13	16	24,42 & 54	0.5	2	9	0
Hypoxic with no main gas flow	0.5	13	16	24,42 & 54	2.0	0	36	0
Hyperoxic with 60/ 40 main gas flow.	2.0	13	16	24	0.5	2	9	6
Hypoxic with 60/ 40 main gas flow.	0.5	13	16	24	2.0	0	36	6
Hyperoxic with 40/ 60 main gas flow.	2.0	13	16	42	0.5	2	9	12
Hypoxic with 40/ 60 main gas flow.	0.5	13	16	42	2.0	0	36	12
Hyperoxic with 32.5/ 67.5 main gas flow.	2.0	13	16	54	0.5	2	9	13
Hyperoxic with 32.5/ 67.5 main gas flow.	0.5	13	16	54	2.0	0	36	13

Table 1. Conditions for simulation of emergency bailout scenarios.

3.0 RESULTS

3.1 Table 2 shows the maximum and minimum PO_2 reached for each scenario. The shaded areas reveal those scenarios where the PO_2 was either lower than 0.16 ATA or higher than 2.5 ATA. No hypoxia was observed in any hyperoxic scenario and vice versa. The only NATO gas that does not violate the PO_2 range is 60/40.

3.2 In all cases the volume of gas in the counterlung was adequate for the diver's breathing demands.

Scenario	NATO Gas Mixture (O_2%:N_2%)							
	100:0		60:40		40:60		32.5:67.5	
	Hypoxic	Hyper-oxic	Hypoxic	Hyper-oxic	Hypoxic	Hyper-oxic	Hypoxic	Hyper-oxic
24 metres - with no main gas flow.	0.27	2.46	0.19	2.0	0.15	2.0	0.13	2.0
42 metres - with no main gas flow.	0.26	2.75	0.18	2.24	0.11	2.0	0.10	2.0
54 metres - with no main gas flow.	0.27	2.87	0.16	2.34	0.11	2.08	0.08	2.0
24 metres - with 60/40 main gas flow.	0.31	2.41	0.23	2.0	0.19	2.0	0.18	2.0
42 metres - with 40/60 main gas flow.	0.29	2.65	0.22	2.21	0.19	2.01	0.16	2.0
54- metres - with 32.5/67.5 main gas flow.	0.29	2.73	0.21	2.29	0.16	2.06	0.15	2.0

Table 2. Minimum PO_2 levels reached during hypoxic scenarios and maximum PO_2 levels reached during hyperoxic scenarios in the simulated CCDA breathing loop under varying initial depth and gas flow conditions. Shaded areas show where PO_2 exceeded the range between 0.16 and 2.5 ATA.

4.0 DISCUSSION

4.1 The Bailout calculations assume that the CCDA is fitted correctly. Gas escaping through the facemask from the diver's nose and mouth could result in a marked decrease in the O_2 content within the breathing system. This would be reflected as an increase of Q_{ex}. A good fit and seal around the diver's mouth are very important and little nasal exhalation is permissible.

4.2 Should the main supply fail, the diver can no longer use his main bypass valve, and must wait for the Bailout flow to fill the counterlung. The addition of a Bypass Valve on the Bailout system would help eliminate this potential problem. Although the Bailout may benefit from a bypass valve, the quick change over of gas may change the selection of bailout mixture as well as the bailout procedures. An additional disadvantage would be the increase in equipment complexity and cost.

4.3 The addition of a separate emergency gas supply to the CCDA will reduce the likelihood of a diver's reserved gas being depleted by undetected leaking. However, the problem of detecting that the main gas supply has failed or is exhausted still remains with the diver. As with the J-valve reserve mechanism of the original CCDA, a diver who does not pay attention to the status of the main supply could run out of gas without detecting the problem. The result would be an unconscious diver. Therefore, it is still important for Clearance Divers to remain aware of this problem. Divers must also be aware that the Bailout bottle post-valve may be activated inadvertently causing a loss of emergency gas.

4.4 When examining the model, consideration was given to the effect each variable has on the resulting PO_2 reading. For example, the sensitivity of PO_2 to maximum system volume was small compared to the influence of initial PO_2 or ascent rate. In general, however, the model appears robust and could be used for modelling other re-breather apparatus. The model could be improved by including separate volumes for the diver and the counterlung and considering the production and removal of carbon dioxide.

5.0 CONCLUSION

5.1 Considering the gasses available, the most likely scenarios that the diver might encounter, and assuming that the CCDA divers will operate their sets correctly, it is concluded from the computer simulation that the most suitable gas to use as a Bailout mixture for CCDA is a 60/40 O_2N_2 mixture using a 10.5 $L \cdot min^{-1}$ (STPD) flow rate.

6.0 RECOMMENDATIONS

6.1 It is recommended that:

a. a 60/40 O_2N_2 mixture with a 10.5 $L \cdot min^{-1}$ (STPD) flow setting be used with the CCDA as a Bailout.

b. the cylinders used for the CCDA Bailout be marked with the NATO marking for a 60/40 O_2N_2 mixture [10] as described by the Experimental Diving Unit [11].

c. the existing CUMA Bailout assemblies be used to deliver the Bailout to the diver. By using the existing assemblies the 11.5 $L \cdot min^{-1}$ (STPD) flow setting set when using a 70/30 O_2/helium mixture with CUMA will equate to a 10.5 $L \cdot min^{-1}$ (STPD) setting when using a 60/40 Nitrox mixture.

d. a further review of the Bailout cylinders, assemblies and gas mixtures be carried out with a view to incorporating a By-Pass valve in the system.

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The Canadian Clearance Diving Breathing Apparatus (CCDA) is a closed/semi closed circuit oxygen/nitrogen minecountermeasures re-breather diving set. Since 1991 a Bailout assembly has been available to the CCDA and by the spring of 1993 all CCDA's held by both Fleet Diving Units had been modified to accept the bailout assembly.

The objective of this investigation was to select which of the four standard oxygen/nitrogen breathing gasses used in NATO could be used with the Bailout without modifications or additional capital expense.

To analyze the data a computer spreadsheet was constructed so that gas flow rates, oxygen consumption, ascent rates, depth changes and other variables could be added or changed throughout a simulated dive scenario.

After looking at the four available NATO diving gasses, the simulation showed that only one of the four gasses, a mixture of 60% oxygen and 40% nitrogen, would be suitable for use as a Bailout gas for the CCDA over the full depth range of 0 to 54 metres. The gas flow rate selected was 10.5 standard litres per minute.

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Canadian Clearance Diving Apparatus
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Rebreather Apparatus
Spread Sheet
NATO Gasses
Flow Rate