Defence Research and Development Canada	Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

A baseline air quality assessment onboard a Victoria class submarine:

HMCS Windsor

Major Y.D. Severs

Defence R&D Canada – Toronto
Technical Report
DRDC Toronto TR 2006-087
May 2006

Canada

A baseline airquality assessment onboard a Victoria class submarine

HMCS Windsor

Major Y.D. Severs

Defence R&D Canada – Toronto

Technical Report

DRDC Toronto TR 2006-087

May 2006

Principal Author

Original signed by Major Y.D. Severs, CD, PhD

Major Y.D. Severs, CD, PhD

Approved by

Original signed by Dr. Shek, PhD

Dr. P. Shek, PhD

Head, Operational Medicine Section

Approved for release by

Original signed by K. M. Sutton

K. M. Sutton

Chair, Document Review and Library Committee

Abstract

In 1998, as part of the management plan for the purchase of the Royal Navy (RN) Upholder Class Submarines (subsequently designated Victoria class), initiatives for submarine air quality were identified. This air quality study is a continuation of this plan; with the objective to obtain information to assist in confirming the status of the submarines and what future air quality management was necessary. This trial thus represents a baseline habitability evaluation of Canada's Victoria class submarines to confirm compliance with the current maximum permissible contaminant limits stipulated in the Air Purification Standard, BR 1326, and how that can best be achieved. To achieve this aim the study monitored the effects of: air purification capabilities (management of Oxygen (O_2) and Carbon Dioxide (CO_2)); routine housekeeping procedures (cleaning and cooking); lifestyle effects (smoking); system effects (engine, compressor and motor); and the effectiveness of snorting, the resulting air exchange and the reliability of monitoring instruments. Monitoring the atmospheric conditions has shown that under normal routine operational conditions, following standard operating practices and procedures, all contaminants found in the atmosphere were within limits set in BR 1326. However, when there are unexpected contributions of contaminants, such as the intake of engine backfire emissions, combustible by-products and key aromatics (i.e., Benzene, Toluene, Ethylbenzene and Xylenes) remain within limits, but the total allowable organics limit is exceeded (40 mg/m^3). Thus, under normal operations contaminant levels are within maximum permissible limits. Findings would therefore indicate that exceeding the standard is not considered a routine occurrence and can be attributed to the engine backfire that occurred while snorting. Maintaining contaminants within specifications when dived are difficult at best, but more so when non-routine events occur that unexpectedly contribute an unknown quantity of contaminants. This can be attributed to many factors; air purification measures are minimal (CO_2 and O_2 only), poorly placed and antiquated, and there is a lack of exhaust ventilation. Further, there is poor to non-existent air exchange compounded by compartmentalization, pocketing in the Weapon's Storage Compartment, and current contaminant measurement devices have been shown to be prone to measurement errors. There is also a lack of guidance for the degradation timeline of the atmosphere, replacement schedules for CO_2 canisters and O_2 candles, and no formula to accurately predict replacement. Therefore, guidelines to assist in maintaining air quality are open to interpretation. Although atmospheric conditions were found to be within specifications during routine operations, to successfully manage submarine air quality, ensure the health and safety of the submariner, and support the conduct of efficient operations, especially during unexpected contributing events, we need to look beyond compliance with regulations. Continued research is necessary to enlighten everyone involved, to guide development of submarine atmospheric policy and procedures and future instrument selection, and to validate the feasibility of atmosphere improvement through engineering changes. As well, improved habitability requires a CO_2 canister replacement efficiency review with associated replacement schedules provided, and a toxicological review of all items intended for use onboard prior to purchase, with a general record maintained in a materials toxicity guide. An ongoing review and operational platform testing of adequate technologies for the accurate and reliable monitoring of contaminants under the harsh conditions of the submarine is also necessary.

Résumé

En 1998, le plan d'administration de l'achat des sous-marins de classe UpHolder de la Marine Royal (RN) (ensuite désignée par classe Victoria) mentionnait des initiatives pour s'assurer de la qualité de l'air. Cette étude de référence sur l'habitabilité des sous-marins de la classe Victoria est une suite de ce plan; ayant pour objectif d'obtenir de l'information afin de savoir si cet environnement rencontre les normes de santé au travail et quel sera le plan d'action du control de la qualité de l'air. Cette étude évalue dans un premiers temps la conformité des concentrations des contaminants atmosphériques, mentionner dans le manuel des normes d'épuration de l'air, BR 1326, puis dans un deuxième temps la façon la plus efficace de rencontrer ces normes. Cette étude à évaluer différent aspects de la qualité atmosphériques : la capacité de purification déjà installer abord (comme le control de l'oxygène (O_2) et du dioxyde de carbone (CO_2)); les activités routinières (nettoyage et cuisson); les effets des activités des membres d'équipages comme le tabagisme; les effets des différents systèmes mécanique (moteur, compresseur); ainsi que l'efficacité de la marche au schnorchel (l'échange d'air ainsi que la fiabilité des instruments de contrôle). La surveillance des conditions atmosphériques a démontré que pendant les conditions normales d'opération, en suivant les normes d'opération, les concentrations de tous les contaminants ont été en dessous des limites fixées par le BR 1326. Cependant, lorsqu'un évènement inattendue, comme dans des conditions de réintroduction de gaz lors d'un «backfire» de moteur, provoque une augmentation des sous-produits de combustion ainsi que les composés aromatiques clés (benzène, toluène, éthylbenzène et xylène). La concentration de ces composés demeure, toutefois, en dessous des limites établies, mais la somme de ces composés dépasse la limite permise (40 mg/m^3). Donc lors de conditions normales d'opérations, les contaminants atmosphériques sont en dessous de limites établies. Les résultats démontrent que le dépassement des normes n'est pas un évènement récurrent et que ce dépassement des limites est ultimement attribuable au «backfire» en marche au snorchel. Maintenir la concentration des contaminants à l'intérieur des limites établies est difficile même dans les meilleures conditions. Cela peut-être attribué a plusieurs facteurs : les contrôles de qualité atmosphérique sont minimal (CO_2 et O_2 uniquement), les appareils de contrôle sont placés à des endroits non favorable et sont technologiquement dépassé, et la ventilation est déficient puisqu'il n'y a pas de ventilation d'échappement. L'échange d'air à l'intérieur du sous-marin est un autre facteur qui complique la qualité atmosphérique; l'échange d'air est faible sinon inexistant a cause de l'effet de compartimentation. L'effet de compartimentation crée des poches d'air dans le compartiment de stockage de armes. Les appareils de mesures de contamination atmosphériques sont sujets aux erreurs de lecture. Il y a un manque de directive claire sur la dégradation de l'atmosphère en fonction du temps, l'horaire de changement de réservoirs filtrants de CO_2 et des chandelles d'0_2 et il n'existe aucune formule précise afin de prédire leur remplacement. Donc, les lignes directrices afin de maintenir la qualité d'air sont sujettes à interprétation. Même si les conditions atmosphériques ont été trouvé satisfaisant lors des opérations de routine, afin de maintenir la qualité de l'air, de s'assurer de la santé et la sécurité des sous-mariniers, et supporter une conduite efficace des opérations, nous devons agir au delà du respects des normes. Un programme de recherche continue est nécessaire afin d'impliquer la communauté des sous-marinier, afin de guider le développement des normes de qualité, afin de s'assurer que la sélection des futurs appareil de contrôle répond aux normes de CF, et afin d'évaluer la faisabilité d'améliorer la qualité atmosphérique par des modifications d'ingénieries. De plus, l'amélioration des qualités d'habitabilité demande une révision complète des horaires de remplacements de réservoirs

filtrants de CO_2. Une étude toxicologique sur tout les produit introduit a bord, devrait être maintenu Une étude continue ainsi qu'une plate-forme de test opérationnel est aussi nécessaire afin d'identifié les nouvelles technologies permettant un contrôle atmosphérique plus précis et fiable dans des conditions difficile comme celui des sous-marins.

This page intentionally left blank.

Executive summary

A baseline airquality assessment onboard a Victoria class submarine

Severs, Y.D.; DRDC Toronto TR 2006-087; Defence R&D Canada – Toronto; May 2006.

To assist in developing plans for the air quality management and future submarine life support initiatives in the Victoria class submarines (formerly Royal Navy (RN) Upholder class), DRDC Toronto was tasked to examine the air quality to determine if the atmosphere complied with Air Purification Standard, BR 1326. The objective of this trial was to obtain information to assist in confirming the atmosphere status of the submarines, and what future air quality management was necessary. This trial thus represents a baseline habitability evaluation of Canada's Victoria class submarines to confirm compliance with the current maximum permissible contaminant limits stipulated in the Air Purification Standard, BR 1326, and how that can best be achieved.

This trial represents a baseline evaluation of submarine air quality under operational scenarios that produce a worse-case atmospheric environment. Over 24-hour periods, the functional and detection capabilities of potential replacement analytical instruments for monitoring the atmosphere were assessed and a 'fingerprint' of the contaminants onboard was obtained. A profile of Carbon Dioxide (CO_2) accumulation and Oxygen (O_2) consumption was determined and the effectiveness of air purification (CO_2 scrubbing; O_2 generation; and, snorting) was assessed. In addition, Carbon Monoxide (CO) was monitored and Carboxyhemoglobin (COHb) was measured in representative smokers and non-smokers. To assess the health hazard potential of aerosolized particles and organic compounds derived from cooking, smoking, and diesel fuel and exhaust gases, concentrations of respirable airborne particulates and volatile organic compounds were measured.

Monitoring the atmospheric conditions has shown that under normal routine operational conditions, following standard operating practices and procedures, all contaminants found in the atmosphere were within limits set in BR 1326. However, when there are unexpected contributions of contaminants, such as the intake of engine backfire emissions, combustible by-products (CO_2 and CO) and key aromatics (i.e., Benzene, Toluene, Ethylbenzene and Xylenes) remained within limits, but the total allowable organic limit was exceeded (40 mg/m^3). Thus, under normal operations contaminant levels are within maximum permissible limits. Findings would therefore indicate that exceeding the standard is not considered a routine occurrence and can be attributed to the engine backfire that occurred while snorting. Despite the fact that CO_2 and O_2 concentrations fell within acceptable limits, the study confirmed that air purification measures on this class of diesel submarines are minimal and poorly placed and there is a lack of exhaust ventilation. Poor to non-existent air exchange was compounded by compartmentalization and pocketing effects in the Weapons' Storage Compartment (used as an accommodation space); and, potential replacement contaminant measurement devices have been shown to be prone to measurement errors. There is also a lack of guidance for the degradation timeline of the atmosphere, replacement schedules for CO_2 canisters and O_2 candles, and no formula to accurately predict replacement. Therefore, guidelines to assist in maintaining air quality are open to interpretation.

Although atmospheric conditions were found to be within specifications during routine operations, one needs to look beyond simple compliance with existing regulations to successfully manage submarine air quality in the future, especially in dealing with unexpected contributing events. This is essential to ensure the health and safety of submariners and optimize operational effectiveness. Research initiatives should be continued to assist in guiding the development of supplements to the RN Standard, BR1326, which addresses the operational needs of the Canadian Navy and the greater number of crew. In support of this objective, several recommendations are made to enhance the management of submarine air quality in Victoria class submarines. These include: a review of all parameters governing the design and use of CO_2 scrubbers, including an investigation of scrubbing alternatives and a determination of the effectiveness of all air purification measures; review and operational platform testing of adequate technologies for the accurate and reliable monitoring of contaminants under the harsh conditions of the submarine; the conduct of engineering feasibility studies to investigate the potential installation of filtering units to decrease particulate and volatile organic materials; the conduct of future research on the chemical composition of aerosolized particulates; the establishment of a Materials Toxicity Guide to govern and control materials brought onboard a submarine; and, to help shape future submarine air quality management initiatives, under operational and emergency situations, the conduct of regular air quality assessments of Victoria class submarines operating under worse case operational scenarios to gain data in support of establishing and maintaining a Canadian version of a submarine habitability guide.

Sommaire

A baseline airquality assessment onboard a Victoria class submarine

Severs, Y.D.; DRDC Toronto TR 2006-087; R & D pour la défense Canada – Toronto; May 2006.

Pour faciliter l'élaboration de futurs plans de gestion de la qualité de l'air à bord des nouveaux sous-marins de classe Victoria (d'anciens sous-marins de type Upholder de la Marine Royal (RN)), on a confié à RDDC Toronto a reçu la tâche d'évaluer la qualité de l'air en la comparant aux normes d'épuration de l'air, BR 1326. L'objectif de cette étude était d'obtenir de l'information afin de savoir si cet environnement rencontre les normes de santé au travail et quel sera le plan d'action du control de la qualité de l'air. Cette étude est une évaluation de base sur l'habitabilité des sous-marins de la classe Victoria. Cette étude évalue dans un premiers temps la conformité des concentrations des contaminants atmosphériques, mentionner dans le manuel des normes d'épuration de l'air, BR 1326, puis dans un deuxième temps la façon efficace de rencontrer ces normes.

Cette étude représente un une évaluation de la qualité de l'air lors de scénarios opérationnel qui reproduisent les pires situations du point de vue de contaminations atmosphérique. On a évalué, au cours d'une période de 24 heures, les capacités de fonctionnement et de détection d'instruments d'analyse servant à contrôler l'atmosphère et on a déterminé « l'empreinte chimique » des agents contaminants présents à bord. On a établi un profil de l'accumulation de dioxyde de carbone (CO_2) et de la consommation d'oxygène (O_2) et on a évalué l'efficacité du système d'épuration d'air (épuration du CO_2, production d'O_2 et marche au schnorchel). De plus, on a surveillé la concentration de monoxyde de carbone (CO) et mesuré celle de carboxyhémoglobine (COHb) dans le sang de fumeurs et de non-fumeurs représentatifs. Afin d'évaluer les dangers potentiels pour la santé que posent les particules en aérosol provenant de la cuisson, de l'usage du tabac et des gaz d'échappement et de carburant diesel, on a mesuré les concentrations de particules atmosphériques inhalables.

La surveillance des conditions atmosphériques a démontré que pendant les conditions normales d'opération, en suivant les normes d'opération, la concentration de tous les contaminants ont été en dessous des limites fixé par le BR 1326. Cependant, lorsqu'un évènement inattendue, comme dans des conditions de réintroduction de gaz lors d'un «backfire» de moteur, provoque une augmentation des sous-produits de combustion ainsi que les composés aromatiques clés, (benzène, toluène, éthylbenzène et xylène). La concentration de ces composés demeure, toutefois, en dessous des limites établies, mais la somme de ces composés dépasse la limite permise (40 mg/m^3). Donc lors de conditions normales d'opérations, les contaminants atmosphériques sont en dessous de limites établies. Les résultats démontrent que le dépassement des normes n'est pas un évènement récurrent et que ce dépassement des limites est ultimement attribuable au «backfire» en marche au snorchel. Bien que les concentrations de CO_2 et d'O_2 se situent aussi dans les limites acceptables, l'étude a confirmé que les mesures d'épuration de l'air, dans les sous-marins à propulsion diesel, sont minimales et mal situées et que la capacité de la sortie de ventilation n'est pas suffisante. . L'échange d'air à l'intérieur du sous-marin est un autre facteur qui complique la qualité atmosphérique; l'échange d'air est faible sinon inexistant a cause

de l’effet de compartimentation. L’effet de compartimentation crée des poches d’air dans le compartiment de stockage de armes. Les appareils de mesures de contamination atmosphériques sont sujets aux erreurs de lecture. Il y a un manque de directive claire sur la dégradation de l’atmosphère en fonction du temps, l’horaire de changement de réservoirs filtrants de CO_2 et des chandelles d’0_2 et il n’existe aucune formule précise afin de prédire leur remplacement. Donc, les lignes directrices afin de maintenir la qualité d’air sont sujettes à interprétation.

Même si les conditions atmosphériques ont été trouvé satisfaisant lors des opérations de routine, afin de maintenir la qualité de l’air, de s’assurer de la santé et la sécurité des sous-mariniers, et supporter une conduite efficace des opération, nous devons agir au delà du respects des normes. Les initiatives de recherche doivent se poursuivre afin de faciliter l’élaboration de la norme d’épuration de l’air, BR 1326, qui mentionne les besoins opérationnels de la marine canadienne et son d’équipage plus nombreux. Pour atteindre cet objectif, nous proposons plusieurs recommandations visant à améliorer la gestion de la qualité de l’air à bord de sous-marins de classe Victoria. Ces recommandations comprennent : l’examen de tous les paramètres régissant la conception et l’utilisation de systèmes d’épuration de CO_2, dont l’analyse des facteurs dont on doit tenir compte lorsqu’on établit et met en place les plans de remplacement des réservoirs filtrants de CO_2; l’examen continu des techniques permettant le contrôle précis et fiable des contaminants dans les conditions rigoureuses propres au milieu d’un sous-marin; l’exécution d’études de faisabilité technique, afin d’évaluer l’installation éventuelle de filtres pour réduire les quantités de particules et de composés organiques volatils; la réalisation de futurs travaux de recherche portant sur la composition chimique des particules en aérosol et la détermination de lignes directrices appropriées en matière de particules présentes lors d’opérations à bord de sous-marins; la création d’un guide de la toxicité des substances permettant de réglementer et de contrôler les matières apportées à bord d’un sous-marin; et afin d’aider le développement du programme de qualité de l’air, lors d’opération de routines et d’urgences, la conduite d’études sur la qualité de l’air dans les pires conditions d’opérations afin d’acquérir de l’information supplémentaire afin d’établir et maintenir une version Canadienne du guide d’habitabilité des sous-marins de classe Victoria.

Table of contents

Abstract i
Résumé ii
Executive summary v
Sommaire vii
Table of contents ix
List of figures x
List of tables x
Acknowledgements xi
Objective 1
Introduction 2
Methods 3
Test protocol 3
Sampling and analytical protocol 4
Real-time monitoring 4
Routine air constituents 4
Airborne particulates 5
Long-term monitoring 6
Volatile Organic Compounds 6
Temperature and relative humidity 6
Biological monitoring 6
Carboxyhemoglobin 6
Statistical Analysis 7
Results and Discussion 8
Degradation timeline for Oxygen and Carbon Dioxide 8
Carbon Dioxide changes 8
Oxygen changes 11
Air purification capabilities 12
Variation of Carbon Monoxide and resulting COHb changes 19
Inhalable airborne particulates 21
Organic contaminants 23
Variations in chlorinated compounds 30
Evaluation of onboard detection equipment 30
Recommendations 34
References 37
Abbreviations 38

List of figures

Figure 1. Changes in CO_2 concentrations under patrol state and snort conditions within six working and living areas of the submarine. 9

Figure 2. Changes in O_2 concentrations under patrol and snort conditions within six working and living areas of the submarine. 12

Figure 3. The CO_2 concentration in the living and working areas of the submarine during a one hour and 10 minute snort. 13

Figure 4. Changes in CO_2 concentration and the effects of air purification scrubbing under sonar quiet conditions. Two CO_2 canisters were activated simultaneously in both the Fore Ends (foreword of Bulkhead 34 upper deck WSC) and the After Ends (Motor Room aft of Bulkhead 56) at 2010 and 2410, respectively. 15

Figure 5. Changes in CO concentrations during sonar quiet condition (one motor running, one fan on slow). 20

Figure 6. The total inhalable particulates (> 10 µm) continuously measured in the control room over an 8 hour period. 22

Figure 7. Total Volatile Organic Compound (TVOCs) concentration variation for each collection period in each protocol within the six compartments of the submarine (TVOCs includes over 300 compounds consisting of aromatics, aliphatics and fluorocarbons). 26

Figure 8. Comparison of CO_2 readings between study detection equipment and potential replacement monitors during the three day habitability trial (data includes CO_2 readings during all five protocols, monitoring dived and snort protocols. Replacement monitors also monitored during non-study periods as part of standard operating procedures). 31

List of tables

Table 1. Concentrations of the key Aromatic Hydrocarbons from each of the five study protocols within six compartments of the submarine (All concentrations for each of the compartments are µm/mg^3). 25

Table 2. Fingerprint identification of the top contaminants during 18 hours dived under sonar quiet conditions after an engine backfire (TVOC levels represent the average total concentration from five samples taken during the 18-hour dived sonar quiet period for each of the compartments). 28

Table 3. Average chlorinated hydrocarbon concentration and sources of atmosphere contamination during an extended 18.5 hour dive during sonar quiet conditions. 30

Acknowledgements

Sincere thanks are extended to the Commanding Officer, Commander D. Mulholland, and crew of HMCS Windsor. There has been a tremendous amount of support given to understand submarine operations, assistance in the collection of data, as well as, assistance in interpreting results to identify the potential sources of contamination. As such, there has been a true collaborative effort to identify the habitability of the Victoria class submarine, beyond having the research team feel welcome by submariners.

A special thanks and acknowledgement are also extended to the DRDC Toronto Preventive Medicine technicians, PO1 Larry Melanson and Sgt Stephane Parent. Their significant technical contributions; commitment to understand the platform; and, unyielding efforts to prepare, assist in data collection and collation were outstanding. Without their efforts and technical expertise this complicated and demanding trial would not have been possible. Special thank you is also extended to Capt Eric Drolet for his assistance in performing the statistics from the data collected.

This page intentionally left blank.

Objective

At the request of Maritime Forces Atlantic (MARLANT) Headquarters, DRDC Toronto Health Hazards Group (HHG) was tasked by MARLANTHQ N37 to provide a baseline habitability evaluation of Canada's Victoria class submarines to confirm compliance with the current maximum permissible contaminant limits stipulated in the Air Purification Standard, BR 1326 and how that can best be achieved [1].

To adequately fulfill the tasking requirement, the following objectives were identified:

1. to identify and quantify the contaminants present onboard and produced on board during a worse-case environmental scenario;

2. to determine compliance with current exposure guideline (BR 1326);

3. to identify the degradation timeline for Oxygen (O_2) and Carbon Dioxide (CO_2) based on full complement Canadian Forces (CF) crew numbers;

4. to identify the efficiency of purification capabilities; and,

5. to determine the accuracy of current operational exposure monitoring capabilities.

The overall intent of this and future submarine habitability studies, is to provide the Navy with information and guidance of air quality onboard diesel submarines to:

1. assist operational managers in:
   a) maintaining an acceptable atmospheric quality onboard submarines;
   b) developing and maintaining a reliable atmosphere-monitoring policy;
   c) establishing a submarine smoking policy;
   d) developing smoke clearance procedures;
2. provide the medical community with an atmospheric snapshot of the submarine environment; and,
3. provide recommendations for reliable and accurate atmospheric monitoring equipment.

Introduction

In 1998, as part of the management plan for the purchase of the Royal Navy (RN) Upholder Class Submarines (subsequently designated Victoria class), initiatives for submarine air quality was identified [2]. This air quality trial is a continuation of the planned initiative to provide a baseline habitability evaluation of Canada's Victoria class submarines to confirm compliance with the current maximum permissible contaminant limits stipulated in the Air Purification Standard, BR 1326, and how that can best be achieved [1]. The standard to which compliance and guidance is based is a RN publication that has been adopted by the CF.

To achieve the desired results of the management plan the trial design was created to assess realistic operational scenarios that create a worse-case atmospheric conditions. Relatively speaking, a worse-case scenario will represent peak degradation of the environment as it applies to respirable quality of the atmosphere. Thus, evaluation of air quality while submerged for 24-hours, with little to no ventilation, will provide an up-to-date fingerprint of the contaminants present onboard, and allow comparison with the Standard, BR 1326 to assess compliance. Further, to broaden the scope of the study to help address any procedural and policy changes, the study also monitored the effects of: air purification capabilities; routine housekeeping procedures (cleaning and cooking); lifestyle effects (smoking); system effects (engine, compressor and motor); and the effectiveness of snorting, the resulting air exchange and the reliability of monitoring instruments.

While current information on submariners' exposure to contaminants can assist in accurately determining potential health effects, it can also assist in evaluating any apparent degree of degradation in performance which could adversely affect operational capability. Thus, collection of accurate data of atmospheric conditions provides much needed information for corroborating current policies and procedures and for substantiating recommendations for altering existing Standard Operating Procedures (SOPs) to prevent any potential reduction in operational capability attributable to submariner exposure to contaminants, now and in the future, over and above identifying compliance.

Methods

To assess air quality compliance with Standard BR 1326, "Air Purification in Submarines", the protocol was designed to monitor conditions while maintaining all routine operational procedures and policies, including those for air purification and monitoring.

Five Protocols were designed to monitor the identified objectives:

1. Standard Dive, under Patrol conditions- 21:45 - 10:50 hours (13.25 hours) 20-21 September, 2004;
2. Operational Snort- 11:40 –11:58 hours (18 minutes) 21 September, 2004;
3. Standard Dive, under Patrol conditions- 12:30 – 15:15 hours (2.75 hours) 21 September, 2004;
4. Snort to full air exchange- 16:25 – 17:37 hours (1hour 12 minutes) 21 September, 2004; and,
5. Standard Dive under Sonar Quiet conditions- 12:56 – 0700 hours (18 hours 4 minutes) 22-23 September 2004.

Test protocol

This study was conducted onboard HMCS WINDSOR during the period 20-23 September 2004, while performing sea trials as part of the submarine licensing program. The objectives were to: identify and quantify atmospheric contaminants to provide a fingerprint of contaminants; to determine compliance with the current standard, BR 1326; to identify the degradation of air with a full CF crew complement; to identify the efficiency of air purification capabilities; and, to assess the functionality and detection capability of air monitoring instrumentation.

In order to assess air quality compliance with Standard BR 1326, the protocol was designed to monitor conditions while maintaining routine operational procedures and standard policies as predetermined by the submarine squadron, MAROPSGRU5. Throughout the trial, all routine submarine air quality procedures and policies were maintained. These included the air purification initiation and replacement schedules and Draeger monitoring of selected contaminants (CO, CO_2, and O_2) that were taken and recorded by the on-watch Naval Radio Operator. The logged data, obtained and recorded periodically, were later reviewed and compared with the instrument data, recorded continuously and on-line.

As mentioned above, continuous monitoring under patrol conditions for Protocols one and three was achieved over 16 hours, and further continuous monitoring occurred under sonar quiet conditions, for protocol five for a period of just over 18 hours. This enabled a reasonable assessment of the air purification capabilities, routine housekeeping procedures (cleaning and cooking), and lifestyle effects (smoking). Monitoring was continued during the two snort protocol periods to observe and document the effectiveness of snorting and the resulting air exchange.

Sampling and analytical protocol

The compounds selected for measurement criteria during this study were those that could be potentially life threatening or carry a risk of producing long-term chronic symptoms. Since allowable exposure limits to these compounds are documented in Standard BR 1326, their measurement also permitted an assessment of compliance with the Standard.

The following air constituents or contaminants were monitored:

- Carbon Dioxide (CO_2);
- Carbon Monoxide (CO);
- Oxygen (O_2);
- Airborne inhalable particulates < 10 microns; and
- Volatile Organic compounds (VOCs) found in diesel fumes, solvents, lubricants).

These compounds were monitored using real-time specific electronic detection instrumentation and area low-flow sampling pumps established in six (6) pre-determined sampling locations. Additionally, biological uptake of CO was measured by Carboxyhemoglobin (COHb). Thermal comfort parameters of the submarine environment included Relative Humidity (RH) and Temperature readings, which were recorded and monitored at regular intervals throughout the duration of the trial.

Real-time monitoring

Routine air constituents

The measurements of CO, CO_2 and O_2 levels within the submarine environment were continuously monitored in real-time data collection mode, achieved by utilizing the following instrumentation:

- Siemens Ultramat 23 CO Infrared (IR) analyzer, with a maximum detection capability of 500 parts per million (ppm);
- Servomex ADC IR CO_2 analyzer, with a maximum detection capability of 5 %;
- Servomex Model 570 Paramagnetic O_2 analyzer, with a maximum detection capability of 100 %;

Using certified gas standards, three-point calibration curves were performed on all instruments during several phases of the study: prior to the survey; prior to each sampling protocol and upon completion of the protocol (pre-post) ; pre-snort and post-snort protocol and upon completion of the completed sampling protocols conducted during the trial period.

The instrumentation used to monitor the constituents CO, CO_2, and O_2 analyzers were located in the Weapons Stowage Compartment (WSC) which is located on the upper deck Fore End of the boat. The sampling train was configured with separate lines of ¼” polyethylene tubing that traverses from the vacuum pumps in each instrument to the "breathing zone" region of six pre-determined sampling locations throughout the vessel:

- Fore Ends (foreword of bulkhead 34 upper deck WSC);
- Accommodation Space (foreword of bulkhead 34, Senior Rates Mess);
- Accommodation Space (foreword of bulkhead 34, Junior Rates Mess);
- Junior Rates Mess (midship aft of bulkhead 34)
- Control Room (midship, navigation work area); and
- After Ends (Motor Room aft of bulkhead 56).

Air was drawn from each of these sampling locations through the polyethylene tubing to the analytical instruments located in the WSC. Sampling of the aforementioned areas was achieved by utilizing a multi-port switching valve (#40 series, Swagelok, Whitney Co., Highland Heights, Ohio) for each of the instruments to measure CO_2, O_2 and CO, respectively. This switching valve facilitated cyclical 15-minute sampling of air constituents in each sampling area during the entire dive period in concurrence with the applicable sampling Protocols one, three and five. During the snort period, the cyclical switching was increased to approximately every three minutes, as seen in Protocols two and four.

During the snort protocols, routine operational conditions required Bulkhead 56 to be shut during a snort. Thus, the rotational monitoring of the air constituents in the motor room (i.e., $CO_{2,}$ O_2, and CO) could not be monitored in the cyclic nature as per all other compartments. To maintain compliance with safety and operational conditions, and so as not to falsely alter the changes in atmospheric conditions that could normally be seen, monitoring of the motor room occurred when the hatch was opened by crew as part of their inspections during the snort. This resulted in four samplings that occurred every 15 minutes for a period of 5 minutes.

All air constituent measurement data were continuously collected through a data logger (Almemo 3290-8 Ahborn Mess, Holzkirchen Germany) onto a Toshiba Tecra 8100 laptop computer (Toshiba, Japan) and stored for future analysis and retrieval.

Airborne particulates

Inhalable airborne particulate concentrations (<10 micron diameter) were measured and data-logged in real-time using an aerosol particulate monitor (Dust-Trac, TSI Incorporated, Environmental Measurements, Shoreview, Minneapolis USA). The total concentration of inhalable particulates was monitored, measured and recorded in the following areas with applicable sampling durations:

- Motor Room and near the ladder to the lower motor room: 3 minutes;
- Control Room, on the navigation table: 8 hours.

Long-term monitoring

Volatile Organic Compounds

To provide a fingerprint of the Volatile Organic Compounds (VOCs) such as those found in diesel fuels, solvents and lubricants, samples were collected on Thermal Desorption (TD) tubes. Knowing from previous trials that toluene, a component of diesel exhaust and solvents, would very likely be present in the highest concentration and thus would have the highest break-through, the collection times for each of the tubes was calculated based upon the expected toluene concentration and break-through time [3]. Thus, the collection time for each of the TD tubes was 4 hours. Sample collection was initiated at the beginning of each protocol and collected for the entire period for each of the protocols at a maximum of four-hour intervals.

Using the Gillian Model LFS-113DC low-flow air sampling pumps with in-line sampling media (as described above) samples were collected at a sampling air flow rate of 40 ml per minute and pumps were pre- and post-calibrated to ensure sampling accuracy and pump efficiency for each protocol. Samples were collected over a total 35.5-hour time-frame drawing ambient air from the WSC (centre of the torpedo racks, used as bunk space); Senior Rates Mess Accommodation Space (aft compartment); Junior Rates Accommodation Space (aft compartment); Junior Rates Mess (near opening to the galley); Control Room (midship, navigation work area); and After Ends (Motor Room, centre workstation).

All tubes were forwarded to the contract laboratory (Cassen Group Inc) and analyzed using Gas Chromatography (GC), Flame Ionization Detection (FID) using NIOSH Method 1501, Issue 2-8/1594 [4], and Mass Spectrometry.

Temperature and relative humidity

The ambient environment of the vessel was monitored using the Q-.Trac (TSI Incorporated, Environmental Measurements, Shoreview, Minneapolis USA). Parameters measured were Relative Humidity (RH) and Temperature that are normal indicators of thermal comfort environmental factors. The duration of sampling and locations were the control room for 12 hours and the motor room for approximately 6 hours.

Biological monitoring

Carboxyhemoglobin

The body burden accumulation of CO was measured non-invasively by testing expired CO concentrations in exhaled breath from representative volunteer crewmembers (10 smokers and 10 non-smokers). Selection of volunteers was also based upon an assurance that a distributed representative sample group was obtained from the varied working and living areas of the submarine**.** The CO concentrations were then used to calculate Carboxyhemoglobin (COHb) levels.

To facilitate an accuracy of the estimated total body burden of CO, COHb concentrations were determined on each volunteer before sailing; prior to and on completion of each shift, thus approximately every 6 hours. This reflected any accumulation during the course of their duties and while at rest. Breath samples were also taken immediately prior to snorting and at the end of the snort protocol; and, on completion of the trial. Test volunteers were supplied with their own collection bag that was evacuated and purged with Nitrogen (N_2) after each use. Timings of sample collection were adjusted to coincide with work and sleep schedules; therefore not all samples were taken simultaneously.

To ensure the collection of deep lung samples (i.e., alveolar air samples), individuals were instructed to take three deep breaths and hold the third breath for a minimum of 15 seconds. The first half of the breath was then exhaled into the environment; the last half was expired into the sample collection bag and subsequently clamped.

Breath samples, once collected, were instantaneously processed for analysis using the Siemens Ultramat 23 CO IR analyzer, ranging from 0 – 100 ppm (Siemens A.G., Karlsruhe, Germany). The analyzer was calibrated by completing a three-point curve, using certified gas standards. The concentration of CO present was then converted to COHb using the following formula: COHb %= 0.16 X CO ppm.

Statistical Analysis

All collected data were reviewed, adjusted for baseline variation, collated and plotted. To determine overall exposure to specific air constituents or contaminants in which continuous real-time data were collected, the ‘area under the curve’ was computed for each area over the time period monitored. Linear regression was performed on CO_2 data for each area to determine the increase in concentration over time.

Results and Discussion

The protocols identified in the methods section were designed to achieve the objective to verify compliance with the Standard, BR 1326, through the identification and quantification of contaminants brought onboard or produced during submarine operations. As well, the findings from the air quality assessment provide further data that identify resulting atmospheric conditions with a Canadian Navy, full-crew complement of 59, that have not been specifically identified within the RN Standard, BR 1326. Thus, the findings from this habitability study can also assist operational managers in the development of policies and procedures in maintaining atmospheric quality onboard the Victoria class submarine that reflect the Canadian Navy's conditions and requirements.

Degradation timeline for Oxygen and Carbon Dioxide

The intent in the first three Protocols was first, to identify the degradation of the environment with a full crew complement; to then identify if an operational snort was able to clear the submarine to limits set within the Standard; and, then upon return to dive conditions, to measure the new baseline and the time to reach limits set within the Standard. The intention was to monitor both CO_2 and O_2 degradation until such time as either the limits of the standard guidelines were reached or the submarine needed to surface to charge batteries.

Carbon Dioxide changes

The Standard BR 1326 indicates that for intermittent exposure to CO2 the Time Weighted Average (TWA) should not exceed an effective concentration of 1.5% over a 30-day period. When ventilating daily, it is recommended that an upper level of 1.75% should not be exceeded and a level of 2% CO2 shall not to be exceeded. These markers were used as the upper limit to determine the timeline for atmospheric degradation. It should be noted that the Maximum Permissible Concentrations (MPCs) set within BR 1326 for O_2 are the same for the emergency exposure limits of 1 hour and 24 hours, as well as for the 90-day operational exposure limit. These limits have been set at 18-22%, with an upper limit set to prevent an explosion hazard rather than an exposure standard [1]**.** Thus, the upper limits set within the Standard for CO_2 concentration have been used as the upper limit marker.

Initial baseline values indicated that the CO_2 concentration in each of the six compartments were 0.07% CO_2 in the motor room, 0.07% in the WSC, 0.21% in the control room, and 0.09%, 0.13% and 0.25% in the junior and senior accommodation spaces and junior rates mess, respectively. These values range from being double and triple to that found in ambient air, which has a CO_2 concentration of 0.035 -0.45%, to over five times that of ambient as seen in the control room and junior rates mess. Thus, these values do not represent ambient CO_2 concentrations. Rather, these initial CO_2 values represent the CO_2 accumulation from crew respiration in a confined space 30 minutes after submergence, and the concentrations vary based on the number of personnel in a compartment at the time of initiation of the study. These values provide the baseline CO_2 concentrations within the six compartments of the submarine for the calculation for timeline for degradation of the environment.

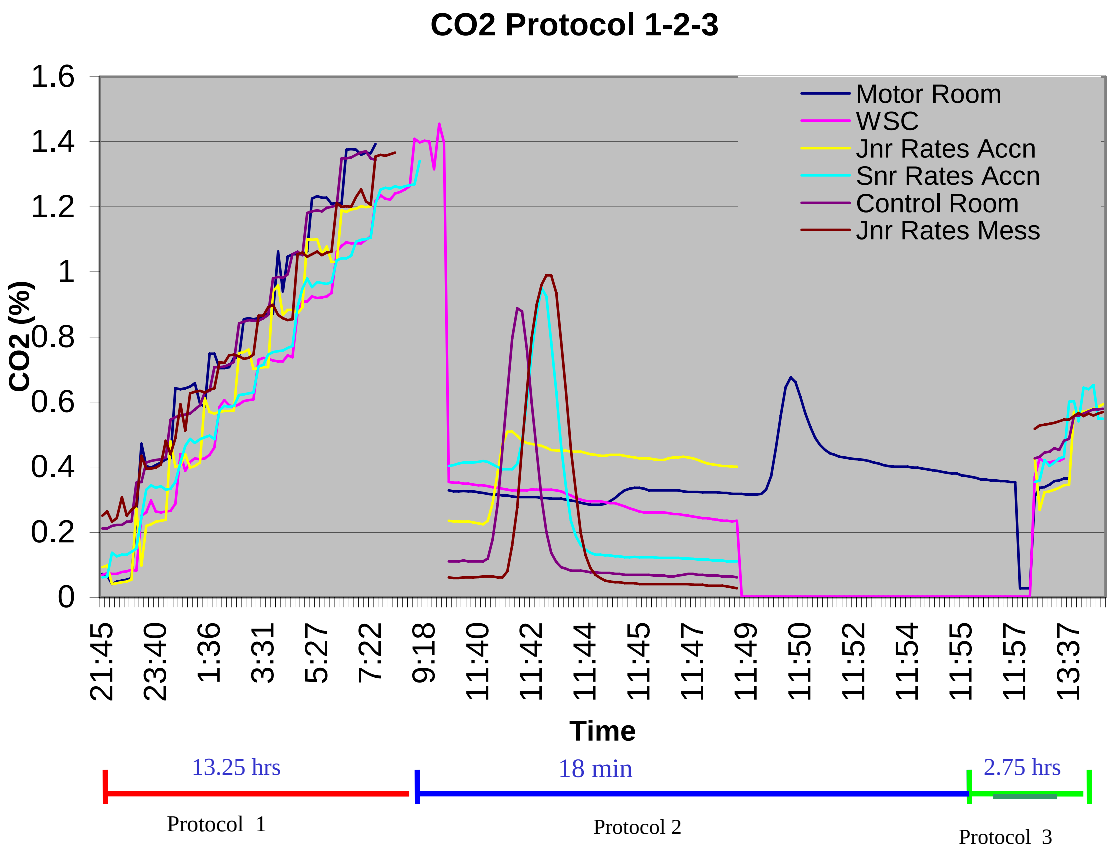

Figure 1. *Changes in CO_2 concentrations under patrol state and snort conditions within six working and living areas of the submarine.*

As seen in Figure 1, the first protocol was monitored without any purification over 13.25 hours with a final average concentration in all of the compartments at the end of the protocol was 1.34%. Specifically, CO_2 concentrations of 1.39% were seen in the motor room and WSC, 1.34% in the senior accommodation space and control room, and 1.20% and 1.37% in the junior rates accommodation space and junior ranks mess, respectively. This increase was not unexpected, as the Standard suggests that with 50 crew a 1% CO_2 concentration would be reached in 7.7 hours. It was projected that with a crew complement of 59 that the upper limit of 1.75% would be reached in 13.5 hours. This calculation has been based upon the prediction guidelines identified in BR 1326, whereby an initial concentration of 0.2% CO_2 with no air purification is assumed. The calculation, as identified in BR 1326, is also based also upon an average respiration rate of 24L/man/hour and a total breathable volume of 1129 m^3 (39870 ft^3). The findings have shown that after 13.25 hours under patrol conditions the recommended ceiling of 1.75% CO_2 was not reached, even without the aid of purification assistance.

Regression analysis indicated, that over the 13.5 hour dive period, CO_2 concentrations increased: 1143 ppm/hr in the motor room (r^2 =.97); 1103 ppm/hr in the WSC (r^2 =.99); 1094 ppm/hr in the junior rates accommodation space (r^2 =.99); 1065 ppm/hr in the control room (r^2 =.99); 1053 ppm/hr in the senior rates accommodation space (r^2 =.99) and 1017 ppm/hr in the junior rates mess (r^2 =.99). The regression coefficient (r^2) would suggest that the linear increase in CO_2 concentration is very strongly time-correlated. These findings would also suggest that increases in CO_2 concentrations are near equal throughout the submarine, which would suggest that over the 13.5 hours dived under patrol conditions that a homogenous mix has nearly occurred. However, results do show that CO_2 increases are greatest in the motor room, then the WSC, the junior rates accommodation space and then the control room. The least increases in CO_2 levels were seen in the senior rates accommodation space and the junior rates mess. Although the differences are not great, they can be explained, in part, by the increased number of personnel found within any compartment at any one time, compared to the other compartments. The second highest increase in CO_2 levels in the WSC would seem unusual. However, as 20 crew members provided breath samples to identify biological uptake of contaminants every six hours in the WSC, taking 30 minutes to one hour to do so, this substantial increase in personnel in the area, although not normally seen operationally, would account for the increase in CO_2 levels. The increased number of personnel would not be the reason for the highest increase of CO_2 concentration in the motor room, as there are routinely only two crew members in that compartment. However, the increased rate of CO_2 accumulation in the motor room can be explained by its proximity to the designated smoking area just forward of Bulkhead 56, with Bulkhead 56 hatch remaining open, and the presence of two blackout curtains just forward of Bulkhead 56 and the smoking area. The blackout curtains would have curtailed any natural air movement from the motor room and smoking area, thus were contributing to the increased rate of CO_2 accumulation.

The second protocol intended to see the clearance of contaminants during an operational snort of 20 minutes, which was identified from operators as reflective of an operational scenario. The intent of measuring the changes in atmosphere pollutants from an ‘operational snort’ was to identify the effectiveness of the timeframe to reduce contaminants throughout the submarine. The results indicate, as would be expected, that the upper deck (not including the WSC) and the junior ranks mess would be cleared quickly, and within 10 minutes they are close to ambient atmospheric levels. Also not unexpected, within the lower deck, was the fact that the junior rates accommodation space took longer to clear.

It should be noted that the peaks seen during the snort, and as well the fluctuations during the dive are not reflective of wide fluctuations in CO_2 concentration. Rather, the fluctuations are a result of the mechanisms used to collect real-time data; cycling through six compartments (alternating every 15 minutes during dived operations and every two minutes during the snort) and the resulting dead space in the lines. The air is drawn through the lines from each compartment to the detection instrumentation, and thus there are a few moments where air from the previous cycle is drawn through the instrumentation. Linear regression calculations have accounted for these fluctuations.

We see in Protocol three (Figure 1), which began immediately upon completion of the snort, that a 20-minute snort does not completely clear the submarine. Upon completion of the snort, as identified in Figure 1, the CO_2 levels were lowest in the motor room at 0.32%, then the WSC at 0.37%, 0.42% in the control room, 0.52% in the junior ranks mess and 0.59% in the junior rates accommodation space. This variation between areas of the submarine after snorting does not quite follow the same pattern of increase as seen when dived. This finding would suggest that clearance within the submarine is least effective in the junior and senior accommodation space. Further, as CO_2 levels have not reached ambient air levels (0.035-0.045% CO_2), this would suggest that further examination of the effectiveness of snorting to clear the atmosphere in all compartments is a necessity, and would suggest that a longer snort is needed to completely clear the entire submarine.

Unfortunately, the third protocol only lasted 2.75 hours as charging of the batteries was required. However, the intent in this protocol was to determine and assess the new CO_2 and O_2 baseline after an operational snort, which was achieved. This protocol also intended to assess the purification capabilities. However, as the protocol only lasted for 2.75 hours as the boat needed to surface to charge the batteries, initiation of purification measures was not necessary as CO_2 levels only reached an average concentration of 0.6% in the submarine.

Oxygen changes

In the same protocol series oxygen was also monitored over a 13.25 hour period and the O_2 levels were fairly consistent within the boat, averaging at 19.6% at the end of the protocol (Figure 2). The levels are well below that of ambient air (20.9%), but fall well within the limits of the Standard (18-22%). This reduction was also as anticipated, as BR 1326 indicates that with 50 men onboard with no purification assistance, o O_2 levels of 18% would be reached in 22 hours for this class of submarine. Again, as identified earlier, the prediction equation was based upon the criteria identified in BR 1326, using an average ventilation rate of 28L/man/hour and a total breathable volume for this class of submarine (1129 m^3 or 39870 ft^3).

However, as O_2 depletion and CO_2 increases are based on respiration and thus inexplicitly linked, the Standard provides a maximum limit for CO_2 as a guideline and does not suggest a limit for O_2. The only guideline provided for O_2 levels within BR 1326 during continued submergence is that these levels should be maintained between 152 mmHg and 160 mmHg. The Standard also indicates that at no time should O_2 levels be allowed to drop below 137 mmHg (18%). These partial pressure guidelines are based upon the measurement of the actual atmospheric pressure within the submarine at the time of measurement. As pressure can fluctuate in a submarine, as seen during the vacuum produced during snorting, BR 1326 indicates that to assess physiological effects from exposure, the effective concentration of contaminants is to be determined by the equation: measured concentration X actual pressure (mmHg)/760 mmHg.

In comparing the O_2 levels identified during the sea acceptance trials performed by the RN for this class of submarines after a dive period of 12 hours, O_2 concentrations were found to be 146 mmHg in the after-escape flat (motor room) and 142 mmHg in the control room, with an atmospheric pressure of 774 mmHg [5]. This would equate to O_2 concentrations of 18.9% and 18.3%, effectively. It is also assumed that a full crew complement of 49 was aboard, although the reports do not identify the number of crew. These findings are much lower than the findings from this study. However, the reported findings have indicated difficulties with instrumentation (having used an *Oxywarn*) [5]. Difficulties and inaccuracies with instrumentation in a submarine is not uncommon as harsh conditions from pressure differentials, water vapour and interfering contaminants can interfere with the functioning and accuracy of instrumentation [3, 6]. Therefore, the accuracy of the data from the sea acceptance trials can be considered somewhat questionable as the confirmation of accuracy of instrumentation was made with Draeger tubes, which also have an inherent error of $\pm$ 25% [3]. It would also be reasonable to assume that during a dive, especially after 12 hours with no snorting, that the pressure within the submarine would have been equalized to near normal atmosphere (i.e., 760 mmHg).

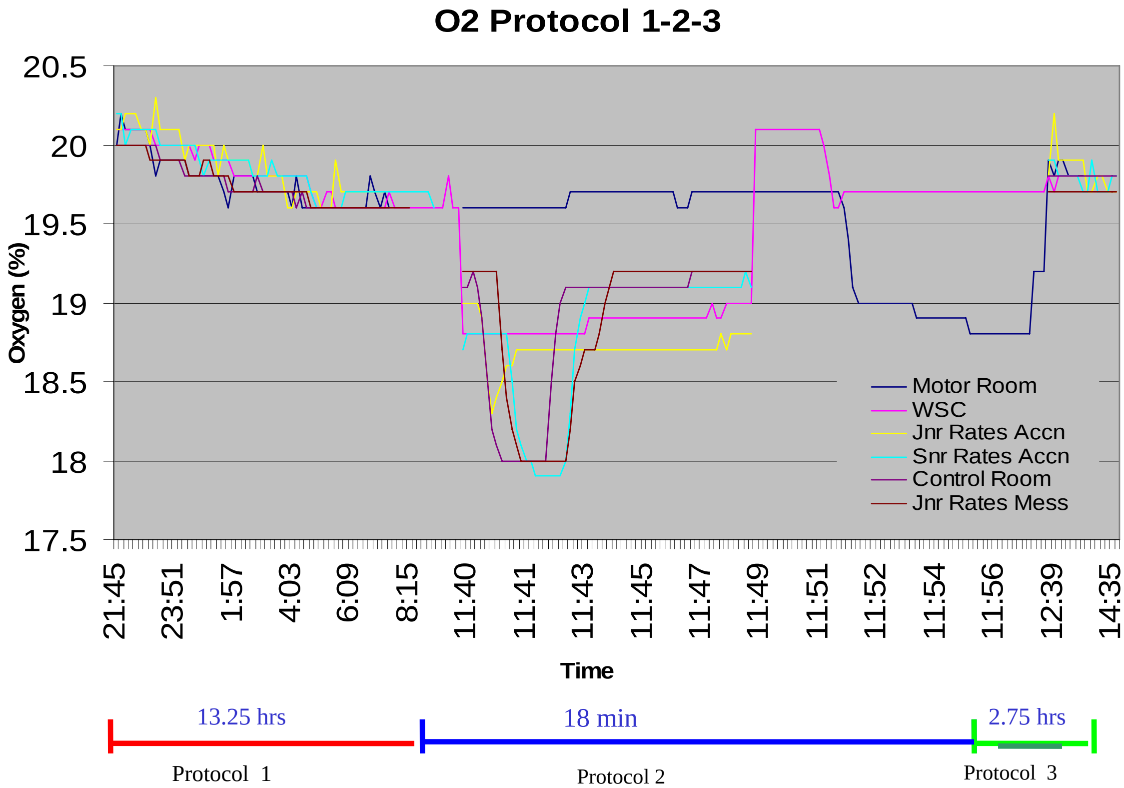

Figure 2. *Changes in O_2 concentrations under patrol and snort conditions within six working and living areas of the submarine.*

After an operational snort of 20 minutes and a return to dive conditions, the O_2 levels did not appear to change significantly (Figure 2). It would be expected that O_2 levels would different from ambient, as results have shown that ambient CO_2 levels within the submarine are not achieved in 20 minutes. The data suggests very little change in O_2 levels upon return to patrol dive conditions after the snort, as O_2 levels only rose to 19.9% O_2 from 19.6%. The initial CO_2 concentrations measured at the start of Protocol three, and guidance from the standard would suggest that the O_2 levels should have been slightly higher after the snort (over 20%). Although calibration and validation with known concentrations of O_2 was performed prior to the initiation of this protocol to confirm reliability of the instrumentation, as identified earlier, accurate monitoring within a submarine can be difficult during real-time operations as instrumentation within industry were not developed for these conditions. Upon re-calibration and verification with confirmed oxygen concentrations a drift of 0.3% O_2 was identified. This would suggest that the initial average starting concentration of oxygen in protocol three would have been 20.2%, which is more in line with expected values.

Air purification capabilities

The purpose of the fourth protocol was to determine the time required to achieve a full air exchange within the boat, and to confirm within this class of submarine that the suggested 35-

minute snort identified in BR 1326 would effectively clear the submarine to ambient air levels. Thus, this protocol was intended to provide operational managers with a timeline of the rate of removal of contaminants, using CO_2 as the indicator. These data could then be used to develop a reduction-of-contaminants curve that would quickly and accurately identify the expected contaminant levels after varied snort times, based upon initial contaminant levels and the ventilation rate. Thus, commanders would have information to guide them in their decisions of snort times by providing the expected state of environmental conditions when snorting ceased.

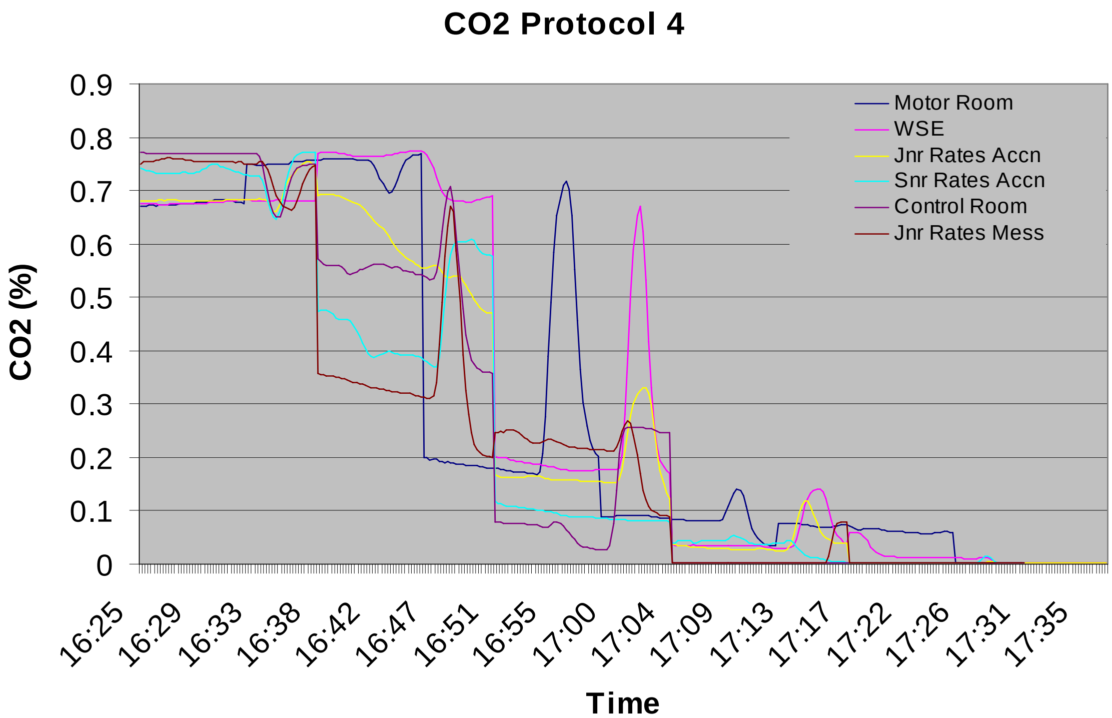

Figure 3. *The CO_2 concentration in the living and working areas of the submarine during a one hour and 10 minute snort.*

As seen in Figure 3, the average concentration of CO_2 on initiation of the full clearance snort was 0.73%. Ideally, to provide guidance to commanders of the clearance of contaminants over time, the levels of CO_2 should commence with the highest level allowable, using the maximum level identified in the Standard of 1.75% CO_2 for intermittent exposure. The resulting clearance curve would then provide the full range of allowable CO_2 levels prior to snort and the resulting concentrations from ventilation. Unfortunately, maximum allowable levels of CO_2 were not achieved prior to initiating this protocol as submergence could only proceed for 2.75 hours before battery charging was required. This is unfortunate, but there is still valuable information provided within this protocol and the one hour and 12 minutes of the snort.

BR 1326 has suggested that a 35-minute snort will effectively provide a complete air exchange within the submarine to ambient atmospheric levels. The study revealed that within the Victoria class submarine this is indeed true; results indicate that after 35 minutes all compartments had levels of CO_2 equal or better than that expected for ambient air. Figure 3 identifies that after a 35-minute snort CO_2 concentrations within the WSC and accommodation spaces were 0.04% CO_2, and the control room and junior rates mess were recorded to be 0.005%. However, levels were not as low in the motor room. After the 35-minute snort the CO_2 concentration was 0.09%, but CO_2 levels were effectively cleared to ambient within one hour to 0.02% (200 ppm).

It may seem odd that CO_2 concentrations would be better than those normally considered as ambient air levels, which typically identifies ambient CO_2 concentrations within the range of 350-450 ppm (0.035- 0.045%). However, the results can be explained by the fact that the submarine was at sea during the snort (beyond the 12 mile limit) and not near any "city pollution" or combustibles. As such, the air was much cleaner than that seen within or around a city. Of note, is that the significant reduction in CO_2 concentrations from a 35-minute snort also meets the levels considered acceptable for compressed breathing air. As there have been considerable difficulties in meeting the compressed breathing air standards for the Built in Breathing System and Emergency Breathing System when charging with air from the confines of the submarine, these findings would suggest that a 35-minute snort prior to charging these systems would be sufficient to meet the compressed breathing standards.

Also, the delayed clearance of the CO_2 in the motor room would initially seem an oddity as the process of snorting with ventilation flowing through the motor room should suggest a full clearance quickly, and one would expect this area to be one of the first to be cleared, as that observed in the operational snort. Although not expected, just prior to ceasing the snort a backfire of the engine occurred, which resulted in an accumulation of combustible gases and diesel effluent. The results have shown that a 35-minute snort will effectively clear the submarine to ambient levels, as suggested in BR 1326, when contaminant generation is sufficiently negligible. Although increases in combustible gases were minimal, the resulting backfire did introduce contaminants and thus ventilation time was increased to reduce the CO_2 concentration to ambient levels. This unexpected outcome clearly identifies the need to monitor selected contaminant levels, especially when contaminants are suddenly introduced, as the time required to effectively reduce the contaminant concentration is based upon a known or confident estimate of the initial concentration.

The final protocol intended to provide a footprint of the contaminants during an extended dive under what would be considered a worse-case environmentally, but also considered operationally realistic. Although there are many varied operational conditions and permutations, a sonar quiet condition was identified as a realistic extended worse-case atmospheric operational scenario that would also meet the additional requirement to perform concurrent sonar trials. As such, routine operational procedures to manage air purification during an extended dive could be monitored for their effectiveness. As well, the resulting engine backfire also provided a unique opportunity to identify the contribution of these contaminants within the submarine, but as well, this outcome provided an opportunity to monitor the distribution and dilution effect of introduced contaminants throughout the boat, with and without purification support during sonar quiet conditions.

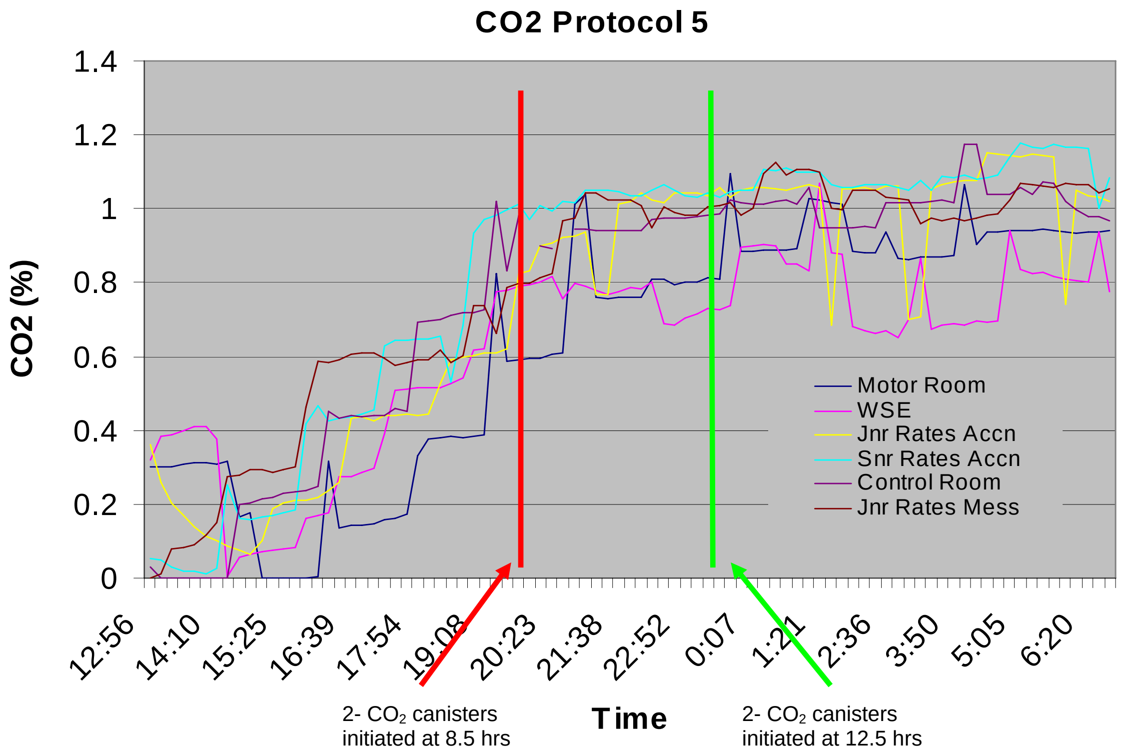

Figure 4. *Changes in CO_2 concentration and the effects of air purification scrubbing under sonar quiet conditions. Two CO_2 canisters were activated simultaneously in both the Fore Ends (foreword of Bulkhead 34 upper deck WSC) and the After Ends (Motor Room aft of Bulkhead 56) at 2010 and 2410, respectively.*

As seen during patrol conditions, routine operational procedures were followed during the sonar quiet submergence. As well, the criteria for surfacing and initiation of the CO_2 canisters were again based upon the criteria within the standard for intermittent exposure to CO_2; when ventilating daily the upper limit of 1.75% CO_2 is permissible. Findings have shown that during the 18-hour dive, in which there was one motor running with one fan on slow (considered routine for these conditions), the resultant rise in CO_2 appears to closely follow that seen under patrol conditions and is in line with the expected concentrations identified in BR1326. Carbon Dioxide concentrations would be expected to be at or around 1% CO_2 in 7 hours. Findings have further shown that just prior to initiating two CO_2 canisters, 7 hours into the extended dive, the effective CO_2 concentration ranged from 1.0% in the junior rates accommodation space, to 0.9% in the control room, 0.8% in the WSC, and an unexpected concentration in the motor room of 0.6% CO_2 (Figure 4). At this time period during patrol conditions while dived (Figure 1), the concentrations varied from 0.9% CO_2 in the WSC, 1.1% in the control room to 1.2% CO_2 in the motor room. The graphs do show a fluctuation in CO_2 concentrations. However, what appears to be a disparity in the motor room CO_2 concentrations between the two protocols is in fact the result of the sample cyclic rotation to monitor the six compartments, as each compartment was monitored for 15 minutes every 1.5 hours. Therefore, single time points cannot be compared for CO_2 levels; rather the data provide an indication of the overall increase of CO_2 over time. Raw data confirms that after 2 minutes, a CO_2 concentration of 0.9% was identified, which would be more in line with what is expected.

A comparative linear regression analysis of the rise of CO_2 concentrations prior to canister activation indicated that over the 7-hour dive period prior to canister activation, the slope of CO_2 concentrations increased to: 1546 ppm/hr in the junior rates accommodation space (r^2 = .96); 1524 ppm/hr in the senior rates accommodation space (r^2 = .98); 1488 ppm/hr in the control room (r^2 = .99); 1467 ppm/hr in the WSC (r^2 = .96); 1350 ppm/hr in the junior rates mess (r^2 = .95); and, 1256 ppm/hr in the motor room (r^2 =.99). Corrections were made to adjust for the variability arising from switching monitoring between compartments. Thus, the regression coefficient (r^2) would again suggest that the linear increase in CO_2 concentration is very strongly time-correlated, although, the increase in CO_2 concentrations during sonar quiet conditions are higher than those seen during patrol conditions.

The explanation for the varied distribution pattern of CO_2 can be attributed to a multitude of factors: sonar quiet conditions provide very little ventilation that is almost non-existent in the accommodations spaces and the WSC; there is no exhaust ventilation present thus there is very little effect on the circulation and dilution of CO_2 concentrations in a compartment; the number of personnel in a given compartment at any given time; and, the contributions from smoking. This lack of ventilation would account for the varied CO_2 increase pattern in sonar quiet conditions than that seen during patrol conditions. Not suprisingly, those compartments with the least ventilation and the greatest number of personnel had the greatest increase in CO_2 concentrations per hour.

However, as there was no additional contribution of CO_2 than that seen during patrol conditions, and the backfire of the engine was shown to have a miniscule contribution of CO_2 levels, other factors must have contributed to the additional increase in the rate of accumulation of CO_2 seen during sonar quiet conditions. The rate of increase in CO_2 concentrations from that seen during patrol conditions could also be due to the increase in temperature in the submarine (30-35 ^{o}C), resulting in increased respiration. The literature suggests that increases in body core temperature of 1.5 – 2 ^{o}C results in a 19% increase in O_2 consumption with a concurrent increase of 18% expired CO_2 [7]. Although body core temperature was not measured, increased CO_2 production provides a plausible explanation for the increased CO_2 production during sonar quiet conditions when all of the factors of environmental temperature, personnel within a compartment and lack of ventilation are considered.

Even with the increase in CO_2 values, results have shown that over the 18.5 hours the CO_2 concentration remained well below the limit of 1.75% with canister activation. Final CO_2 concentrations ranged from 0.93% and 0.96% in the motor room and control room respectively, to 1.02% and 1.08% CO_2 in the accommodation spaces, and 1.05% CO_2 in the junior ranks mess. The lowest readings at the end of the 18.5 hour submergence period were found in the WSC, with a CO_2 concentration of 0.77%. The range of values is consistent with those found in the Oberon class [3], and the variation between compartments can again be attributed to the number of personnel found in each area, the concurrent ventilation conditions, and the location of the CO_2 adsorption units.

We see with the use of the Carbon Dioxide Absorption Units (CDAUs) in which two canisters were initiated in both the Fore Ends (foreword of Bulkhead 34 in the WSC) and the After Ends

(Motor Room aft of Bulkhead 56), simultaneously at 7.2 and again at 11.2 hours into the dive, CO_2 concentrations were effectively maintained or the increase rate was slowed in all areas except the WSC, in which CO_2 levels were reduced with each canister activation. Reduction of CO_2 levels in the WSC is not surprising as the CDAU is in direct proximity to the fairly open space of this compartment (Figure 4). The CO_2 levels in the junior and senior rates accommodation space however increased from 0.9% and 1.01 % CO_2 to 1.05% and 1.03% CO_2 respectively after the first canister initiation, and CO_2 concentrations effectively remained at the same concentration throughout the second canister application. The control room and junior rates CO_2 concentrations also rose slightly from 0.96% and 0.81% CO_2 to 1.01% and .99% CO_2 respectively after 3.5 hours with the first canister. Carbon Dioxide concentrations then changed only slightly to 1.02% and 0.99% after the second 3.5 hours with canisters use. Thus, using two canisters, fore and aft, the CO_2 levels were not reduced significantly but the subsequent rate of accumulation of CO_2 was reduced.

The only true increase in CO_2 concentrations during canister use was in the motor room, whereby CO_2 concentrations rose from 0.6% to 0.81% after the first round of CO_2 canisters and to 0.86% CO_2 after the second. Although the rate of CO_2 increase was the lowest (1256 ppm/hr), the results have shown that CO_2 levels did rise even with canister activation. These results are not as expected as the CO_2 scrubbers are situated just forward of the motor room, forward of Bulkhead 56. This apparent anomaly is likely due to the fact that this area was also the smoking area, and smoking occurred directly over the CDAU. The result was the production of combustibles, which have likely contributed to the subsequent rise in CO_2 concentrations in the motor room as 56-bulkhead hatch remained open during the period. Also, the placement of a blackout curtain to prevent the movement of smoke to the control room, and a further blackout curtain placed forward of that to ensure the maintenance of night vision for those on watch would have impeded the greater effect the canisters may have had in the control room.

Although the soda lime canisters have effectively slowed the rise of CO_2 concentrations, findings have shown that their effectiveness only lasts for 3.5 hours at which point the absorption capacity cannot keep up with CO_2 accumulation, and CO_2 concentrations begin to consistently rise in all compartments of the submarine. Purified air is also not re-circulated. Instead air surrounding the CDAUs is continually redrawn into the absorption units, which decreases its efficiency and capacity to reduce levels within the confines of the submarine. Thus, as in other habitability trials [3, 6], it can be seen that there are inherent problems in effectively reducing the CO_2 concentrations within the submarine because of the location of the CDAU and its mechanism of action.

The ineffectiveness of the CO_2 absorption units was especially evident in the lower deck accommodation spaces which saw the greatest increase in CO_2 levels. Even with continual replacement of canisters, CO_2 concentrations continued to rise although the rate of increase was significantly reduced with canister usage. A multitude of factors, taken together, contribute to this ineffectiveness:

- Placement of the CDAUs on the upper deck and isolation from the living compartments on the lower deck (motor room CDAU further impeded by blackout curtains);
- Poor to non-existent air exchange (under sonar quiet and ultra quiet conditions), with non existent exhaust ventilation;

- Configuration of the junior and senior rates accommodation spaces, specifically the junior rates accommodation space; and,
- Large number of occupants in the accommodation spaces.

Carbon Dioxide levels were maintained well within specifications identified within BR 1326, however, the results cannot be attributed to the air purification guidelines set out in Standard BR 1326. BR 1326 only provides a guide for CO_2 and O_2 management calculations of the expected time to reach 1, 2 and 3 % CO_2 and 18% O_2 concentrations for 30, 40 and 50 men. The BR 1326 Standard does not provide a method to manage the atmosphere using the purification capabilities from the CDAU or the Oxygen Generators. Currently, the standard does not indicate when purification measures should be initiated, how many should be used at any one time, or how often they should be exchanged.

The problem of calculating replacement schedules is not new, suggestions to create a replacement schedule have been previously identified [3, 8], and the issue can still be seen as a problem. Without the aid of detailed guidelines for air purification management the decision to initiate a purification regime relies upon past experiences and onboard detection equipment that is not assured of accurate or consistent results (discussed later in this report). As this class of submarine is the only one of its kind and the only data available, to the authors knowledge, is that for the sea acceptance trials in which CO_2 canister effectiveness were not assessed, there is a further reliance by commanders upon experience that may not be related to this class of submarine. Thus, the decision to initiate purification when CO_2 concentrations reached 1% was based upon the findings and guidance provided in previous habitability trials in the Oberon class submarine [3, 6]. A further decision was made by the commander to assess the capability of the CDAU to aid in air quality management using two canisters per unit rather than four, as there is a very limited supply of soda lime canisters available for daily use. There are only 104 canisters available for daily use, and using 8 canisters every four hours as suggested in BR 1326 would result in a depletion of all canisters within 52 hours. This canister usage would not be considered unusual as maintaining submergence for prolonged periods would not be considered operationally unrealistic.

Therefore, although study findings have shown that the use of two canisters versus four per CDAU reduces the rate of accumulation of CO_2, the availability of CO_2 canisters during prolonged submerged missions without extended snorting to exchange the air presents a concern. The development of detailed policies and procedures to aid in air quality management would be helpful in managing this limited resource, but this does not address the availability of CO_2 canisters and O_2 candles, in addition to the further limitations for storage. Alternate and potentially more effective methods of absorbing CO_2 should also be explored, such as the research in assessing the potential of Lithium Hydroxide absorbing methods currently undertaken by the Experimental Dive Unit at DRDC Toronto.

Oxygen levels were also monitored during the extended submergence during sonar quiet conditions. Findings have shown an average baseline O_2 concentration of 20.4% at the start of the extended, reduced ventilation submergence protocol. While results were consistent with each other, these values can be considered a little lower than expected as a full clearance snort to ambient was achieved just prior to initiation of the dive. Calibration and verification with known concentrations were performed prior to initiating this protocol. Thus, the values were considered reliable after this confirmation. However, values would be expected to be higher when comparisons are made with previous studies [3, 5, and 6].

In further examination of the results over the period and comparing the results with those from patrol conditions in this study, the average concentration of O_2 after 13.5 hours was 19.6%, which is line with predictive equations, while findings for this protocol indicate an average decline to 19.6% O_2 levels after 18 hours. Confirmation of values with known concentrations was performed upon completion of the protocol. Further confirmation with the calculations in the Standard of the expected time to reach 18% O_2 levels, reveal that with 59 men a concentration of 18% O_2 would be expected in 19 hours without purification,. In retrospect, it can be seen that instrumentation detection inaccuracy has occurred. This type of analyzer, using paramagnetic technology, is considered one of the most reliable methods for detecting O_2 levels. However, the literature indicates that this type of detection technology is affected by vibration and temperature fluctuations of the gas [9]. As temperature within the submarine during this protocol was 30-35 ^{o} C, this could account for the inaccuracies, even with verification with known standards. This inaccuracy is indeed unfortunate as presumptions of the need for oxygen purification were based upon O_2 readings, but as identified previously, instrument inaccuracy in these harsh conditions is not uncommon [3, 6]. Thus, these findings would indicate further study is necessary to identify the efficiency of the O_2 candles and their effect to improve O_2 levels throughout the submarine. Further, these findings would also suggest that further examination of detection capabilities of instrumentation and imposing interferences within a submarine (i.e., humidity, temperature, interfering contaminants) are still necessary. A future study onboard the submarine comparing and confirming various detection technologies is recommended to support the requirement to improve current monitoring instrumentation onboard.

Variation of Carbon Monoxide and resulting COHb changes

During the entire study, for each protocol, CO was measured continuously throughout the six compartments of the submarine. In order to determine the lifestyle effects of smoking to the habitability of the submarine, the study did not impose any restrictions to the smoking policy within the boat. Smoking was only permitted in one area of the boat, just forward of Bulkhead 56, in which a blackout curtain was placed between the control room and Bulkhead 56 to limit exposure. Smokers were permitted to smoke at any time, except during routine battery monitoring practices.

In order to identify the body burden of CO as well as the contribution of secondary smoke, 20 volunteers were recruited for breath samples, 10 smoker and 10 non-smokers, from various worksites, and living spaces. Volunteers were not asked to curtail their habits only that they adhere to their current habits while adhering to the policy within the submarine.

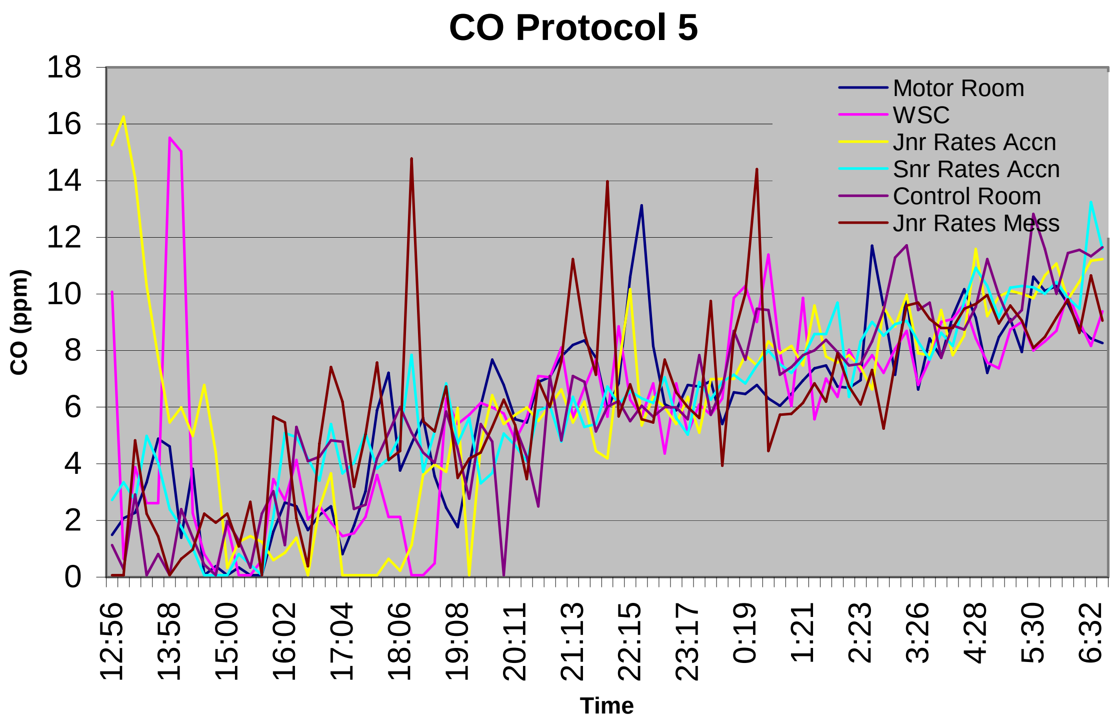

Figure 5. *Changes in CO concentrations during sonar quiet condition (one motor running, one fan on slow).*

Carbon Monoxide is produced from incomplete combustion, arising from fuel combustion, cooking and of course smoking. Throughout the study very little CO was present, which is not surprising as combustion products, beyond smoking, were only present during snorting when the engines were running. Sources of CO produced from cooking were also considered very limited, as deep-frying did not occur. Therefore, it is not surprising that during the entire protocol the CO levels did not exceed the 15-ppm limit identified in Standard BR 1326. Figure 5 shows that within the extended sonar quiet condition CO levels in general slowly rose during the 18-hour period to a maximum of 8-12 ppm in all compartments. These CO levels are well within the 15 ppm limit set by BR 1326. The same slow rise and maximum levels were also seen in Protocol 1 (ranging from 6-9.3 ppm), which is also reflective of previous trials [3]. As the only combustion during this extended dive was essentially the result of smoking which only occurred at Bulkhead 56, and with the reduced ventilation within the boat during sonar quiet conditions, the resulting CO throughout the boat can thus be said to have freely diffused to all compartments. This is evident by the endpoint CO levels of 8.27 ppm in the motor room, 9.38 ppm in the WSC, 11.23 ppm and 11.59 ppm CO in the accommodation spaces, and 11.65 ppm and 9.06 ppm CO in the control room and junior rates mess, respectively. Although an engine backfire had occurred during the snort protocol, CO levels during the sonar quiet condition would suggest that the contribution of CO from this event was minimal, at least from a CO perspective.

The biological uptake of CO, as identified by COHb levels, as expected, was also very low during the sonar quiet condition (averaging 1-3 %), with one smoker achieving a COHb of 6% and another 5%. The levels for non-smokers were no greater than 1%. These levels can be considered normal for the average population of smokers and non-smokers. These low COHb levels also fall well within the acceptable functional limit of 10% COHb set within the guidelines identified by the US Army in Mil Hdbk-759C [10]. The COHb guideline, also used by the CF for Army capital equipment purchase and development, has been based upon research that a maximum exposure which results in COHb levels at or below 10% should not affect the ability of personnel to operate or maintain equipment [10]. Further, research findings on which the guideline has been based have identified that a COHb of 5% should not limit visual perceptions at night. Therefore, COHb levels as identified by the representative smoking and non-smoking crew members should not influence the cognitive or motor functions of the crew.

It is interesting to note from this trial that there were only 15 smokers of the 59 persons onboard the submarine. In previous trials the proportion of smokers was considerably higher; usually at least 50% if not more of the crew were smokers. This perhaps identifies a trend that is comparable with society, in which a smaller proportion of individuals are taking up the habit and more are giving it up.

Results that are unusual that cannot be easily explained were the occasional random surge peak increases of 5-8 ppm CO to levels of 10-15 ppm CO found only in the WSC, control room and junior rates mess. As no engines were running nor was there any cooking occurring (as is normal under sonar quiet conditions), and there was no smoking in these areas, the surge increases in CO are difficult to explain. Calibration and verification of study instrumentation accuracy was completed and checked, and monitoring equipment used onboard was also checked as a confirmation. Carbon Monoxide is produced as a result of combustion, therefore the source of the CO production, although small, was perplexing. Crew have suggested that the source of CO could have been the use of the facilities in the galley (i.e., toaster) by crew members during shift change. However, the cycle of surges does not match, and this does not account for the surges in the control room or WSC. In discussion with the engineers as to where the source of CO would arise, it was agreed, as BR 1326 suggests, that the only source of CO production would be from heating of wires. This increase, although minimal, should be investigated as the cause of heated wiring is only presumed as a plausible explanation for the surges.

Inhalable airborne particulates

A key intent in performing this habitability trial was to determine compliance with the exposure guideline used for the patrol submarine platform, as identified in the Standard BR 1326, Annex A. However, a maximum permissible limit has not been specifically identified in the Annex for inhalable particulate matter. Rather, there is a 0.5 mg/m^3 MPC for 90-day exposure for aerosols. The definition of aerosol has been defined in the Standard, BR 1326 as solid and liquid particles that are suspended in the atmosphere. The definition, and therefore the limit, does not specifically identify the allowable maximum inhalable particulate fractions within the atmosphere. Although there are no guidelines or specifications covering allowable limits specifically for respirable particulates in Standard BR 1326 or any other military standard, to achieve the objectives identified for this habitability trial, particulate samples were collected to identify if respirable contaminants were a concern within this platform.

In referring to the civilian industrial standard for particulate exposure guidance, which governs occupational exposures, the Time Weighted Average-Threshold Limit Value (TWA/TLV) for insoluble particles have recently been removed as they have been considered of low toxicity due to insufficient data to support the recommended levels [11, Appendix B]. Thus, within the American Conference of Governmental Industrial Hygienists (ACGIH)– Threshold Limit Values and Biological Exposure Indices guideline, which the CF has agreed to comply with, there is no longer an applicable TLV for insoluble particles. They do however still assert that particles that are biologically inert, insoluble, or poorly insoluble, and cause no other toxic effect beyond inflammation of the lung, may still cause adverse effects. Thus, rather than a guideline for exposure, the ACGIH now only recommends that the TWA of airborne concentrations should be kept below 10mg/m^3 for inhalable particulates if the above criteria are met.

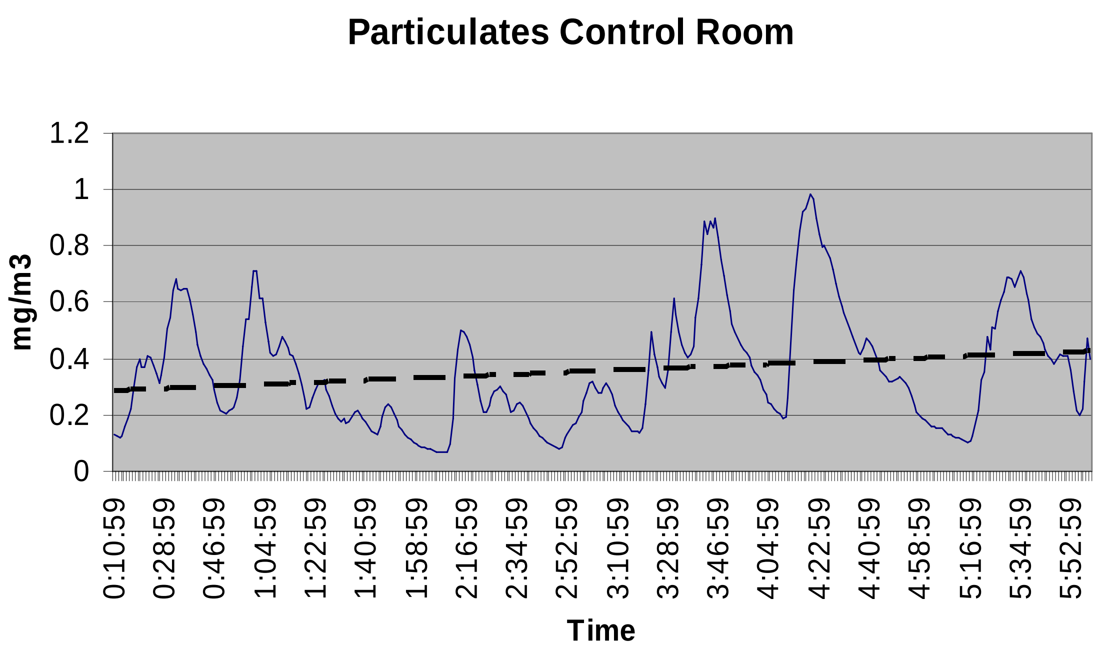

Figure 6. *The total inhalable particulates (> 10 µm) continuously measured in the control room over an 8 hour period.*

It is important however to indicate why this ACGIH recommended limit was selected for exposure comparison and what assumptions needed to be made. It is also important to note that the civilian industrial standard is based upon an 8-hour day, 40-hour week exposure, and given the conditions of submarine operations, it would be inappropriate to simply apply this recommended limit of exposure to this environment. This recommend limit does however provide a convenient yardstick for comparison of inhalable particulate exposure that is not identified within the Standard BR 1326. The industrial inhalable particulate TWA of 10 mg/m^3 limit was chosen, as it is applicable for generic particulates such as those found in diesel exhaust, which do not contain silica or asbestos. As the detector measured quantities less than 10 um but could not distinguish size categories below this value, and as a determination of particulate composition was not available, criteria for inhalable particulates were applied in this study.

The decision to monitor for inhalable particulates was also made as there have been anecdotal suggestions in the past that aerosolized particulates might be a problem [3], and as such, levels were monitored in the motor room and control room as they were considered the most vulnerable areas. As only one monitoring instrument was available, and switching between compartments was not feasible, samples were collected consecutively. It is unfortunate that the instrument was inadvertently turned off in the motor room, thus an insufficient quantity of data were available for analysis (3 minutes) from the motor room. However, the inhalable fraction of particulates (> 10 μm) was collected continuously in the control room for 8 hours.

Results have shown that over the continuously monitored 8 hours, a TWA cumulative exposure of 0.259 mg/m^3 was found in the control room (Figure 6). These levels are lower than those found in the Oberon class submarine, which averaged a TWA particulate exposure of 0.342 mg/m^3 throughout the submarine [3]. Findings are however consistent with the cumulative particulate exposure found in the control room in the Oberon class (0.214 mg/m^3) [3]. Thus, based on the above assumptions, the TWA concentration of inhalable particulates during sonar quiet conditions fell well within the recommended ACGIH guidelines of 10 mg/m^3 [11], but also fall within the 0.5 mg/m^3 permissible aerosol level identified within BR 1326.

One must remember that the ACGIH limit is based on particle size only, assuming the particulates were composed of insoluble material, with no known toxicological effect, beyond inflammation. As these criteria cannot be confirmed from this study, further detailed study of particulates is necessary and should include an analysis of particulate composition. Until this is done, one must be cautious in judging the results and assuming compliance for inhalable particulates.

One of the significant challenges in dealing with air quality in a diesel-electric submarine is still the control of engine exhaust emissions. Examination of the aerosol contribution by the Royal Australian Navy (RAN) in their Collins class has shown that although diesel particulate matter (DPM) levels are within allowable limits, the respirable exhaust particulate contribution was predominantly due to exhaust intake through the induction mast with a minor contribution from fugitive emissions [12]. Review of the DPM literature by Mazurek et al (2005) further indicates that when there is no substantial contribution of DPM from the induction mast, acceptable levels of DPM can be maintained [12]. This would suggest that the majority of DPM contributions result from inherent design problems associated with snorting due to the co-location of the induction and exhaust trunking. A recommendation for system redesign is of course not a reasonable, cost-effective solution, however, operational approaches to snorting can be recommended to reduce aerosol and particulate exposure. The RAN’s approach to reduce aerosol concentrations is to change course when exhaust emissions become apparent. This would seem a reasonable approach to manage and reduce DPM levels, when possible. In order to monitor and control conditions, a capability must exist to detect and monitor the air quality, which currently is not available.

Organic contaminants

To further identify the contaminants brought into the submarine, chemical products that may be off-gassed from the inherent construction, or chemicals produced during operations or lifestyle, samples were collected on a collection media (i.e., Tenax tubes) to identify the contribution of Volatile Organic Compounds (VOCs) into the atmosphere. Identification thus provided an opportunity to identify the accumulation and distribution pattern of VOCs in various areas of the submarine as well as, the efficiency of snorting to remove contaminants. Monitoring and tracking of the dispersion of VOCs within the six compartments of the submarine through all five protocols also provided an opportunity to identify the likely source of the VOC contribution.

Based on the classes of VOCs identified during this study, the pre-dominant group of compounds were the petroleum-based hydrocarbons. Their likely sources are contributions from diesel fuel, motor oil, motor exhaust and petroleum solvents used in cleaning. In general, all fuel oils consist of a complex mixture of aliphatic and aromatic hydrocarbons, comprised mostly of aliphatic alkanes (paraffins) and cycloalkanes (naphthenes) (80-90%), with a consistent smaller proportion of 10-20% for aromatics, such as Benzene [13].

Results from the study have shown that the highest levels of VOCs were those of the key aromatic hydrocarbons, to include Benzene, Toluene, Ethylbenzene and Xylenes (BTEX). As seen in Table 1, Xylenes were found to have the highest concentration followed by Toluene, with significantly lower levels of Ethylbenzene and Benzene. These findings would suggest that the primary source of aromatic hydrocarbon accumulation was not from diesel fuel contribution. This finding is not surprising as excluding Benzene, which is found almost exclusively in fuel and rarely in other products, the other three compounds are heavily used in solvents and degreasers. Xylene contains approximately 20% Ethylbenzene, and besides being a component of fuel, it is found in many petroleum products such as paint solvents, alkyl resins and rubber cement. Toluene is also found in many products such as paints, coatings, oils, resins, adhesives, and detergents, as an example [13]. Therefore, the source of BTEX during the dived protocols would have primarily resulted from the distribution/dilution from the use of petroleum products such as cleaners and degreasers. The contribution of non-combusted fuel components (BTEX) during snorting can be seen as minimal, even with the engine backfire. Regardless, all BTEX components were well below the 40 mg/m^3 limit for total organics in the Standard, as were each individual component. Study findings have thus shown that in each of the five protocols the limits set in BR 1326 for Benzene (1.5 mg/m^3), Toluene (15.9 mg/m^3), Xylenes (17.8 mg/m^3), and Ethylbenzene (20 mg/m^3) were not exceeded (Table 1).

As identified earlier, identification of VOCs collected at the beginning of each protocol and at four hour intervals, as needed, for each protocol provides an opportunity to investigate the distribution of chemicals within the submarine. As seen in Figure 7, the VOC levels in the control room were lower probably due to the better ventilation in this area after snorting (Figure 7, Sample 5-1). In addition, over all of the sampling periods, the WSC contained the lowest amounts of the aromatic compounds; which probably due to its location being farthest away from the motor room where these compounds originated.

Table 1. Concentrations of the key Aromatic Hydrocarbons from each of the five study protocols within six compartments of the submarine (All concentrations for each of the compartments are µm/mg³).

Benzene	Motor Room	Control Room	Jr. Ranks Mess	Jr. Rank Accommodation	Senior Rank Accommodation	WSC	Mean Concentration
Protocol 1-dived	27.8	22.8	27.1	27.0	16.2	19.2	23.3
Protocol 2- snort	14.5	9.0	12.2	16.3	14.4	25.2	15.3
Protocol 3- dived			8.7	23.9	23.8	21.7	19.5
Protocol 4- snort			11.2	16.1	14.9		14.1
Protocol 5- dived	87.5	61.8	45.4	43.5	38.4	15.0	48.6
Mean Concentration	43.3	31.2	20.9	25.3	21.5	20.3	24.2

Toluene	Motor Room	Control Room	Jr. Ranks Mess	Jr. Rank Accommodation	Senior Rank Accommodation	WSC	Mean Protocol Concentration.
Protocol 1-dived	134.7	113.1	126.6	118.5	82.6	87.3	110.5
Protocol 2- snort	61.2	44.2	64.1	102.8	85.5	503.7	143.6
Protocol 3- dived			45.5	159.2	141.0	124.1	117.5
Protocol 4- snort			60.4	89.7	86.8		78.9
Protocol 5- dived	299.3	191.8	288.7	287.9	243.6	87.0	233.0
Mean Concentration	165.1	116.4	117.1	151.6	127.9	200.5	136.7

Ethylbenzene	Motor Room	Control Room	Jr. Ranks Mess	Jr. Rank Accommodation	Senior Rank Accommodation	WSC	Mean Protocol Concentration.
Protocol 1-dived	44.2	32.5	37.8	29.8	24.8	24.0	32.2
Protocol 2- snort	20.3	11.1	18.7	28.0	21.1	39.8	23.2
Protocol 3- dived			12.8	44.1	40.2	37.5	33.7
Protocol 4- snort			16.9	23.9	24.5		21.7
Protocol 5- dived	123.0	79.0	171.6	162.6	142.7	60.5	123.2
Mean Concentration	62.5	40.9	51.5	57.7	50.7	40.4	46.8

Xylenes	Motor Room	Control Room	Jr. Ranks Mess	Jr. Rank Accommodation	Senior Rank Accommodation	WSC	Mean Protocol Concentration.
Protocol 1-dived	246.1	180.9	206.3	163.4	148.1	137.9	180.4
Protocol 2- snort	116.1	69.1	106.5	158.6	119.6	198.6	128.1
Protocol 3- dived		1514.0	75.7	245.7	226.4	211.6	454.7
Protocol 4- snort			93.2	130.5	138.9		120.8
Protocol 5- dived	802.5	482.7	987.9	938.7	815.0	421.4	741.4
Mean Concentration	388.2	561.7	293.9	327.4	289.6	242.4	325.1

Further, the backfire of the engine at the end of the full clearance snort in Protocol four also provided an opportunity to identify the dispersion of VOCs through the submarine created from this event. For discussion purposes, it is important to note the number of samples taken within each protocol. For instance, in Protocol five, not all samples were adequate for analysis, as seen for the motor room (Figure 7). Thus, the calculation for the total VOC concentration over the entire dived period would appear to be lower in the motor room, however, as seen in Figure 7, the highest level of VOCs was found in the motor room during 12 of the 18 hours of the dived period in protocol five. This finding would suggest that the engine backfire at the end of the snort protocol introduced contaminants into the submarine. This is apparent from Sample 5-1 from the motor room, with its highest level of VOCs within the submarine (67.6 mg/m^3). Upon examination, the resulting distribution of the total VOCs from the engine backfire are apparent from sample periods 2-5 in Protocol 5, where over the dived period there is a subsequent decrease in the motor room over time and an increase in total VOCs in the other areas of the boat (Figure 7). These findings would suggest that with very little ventilation. under sonar quiet conditions contaminants passively diffused throughout the submarine.

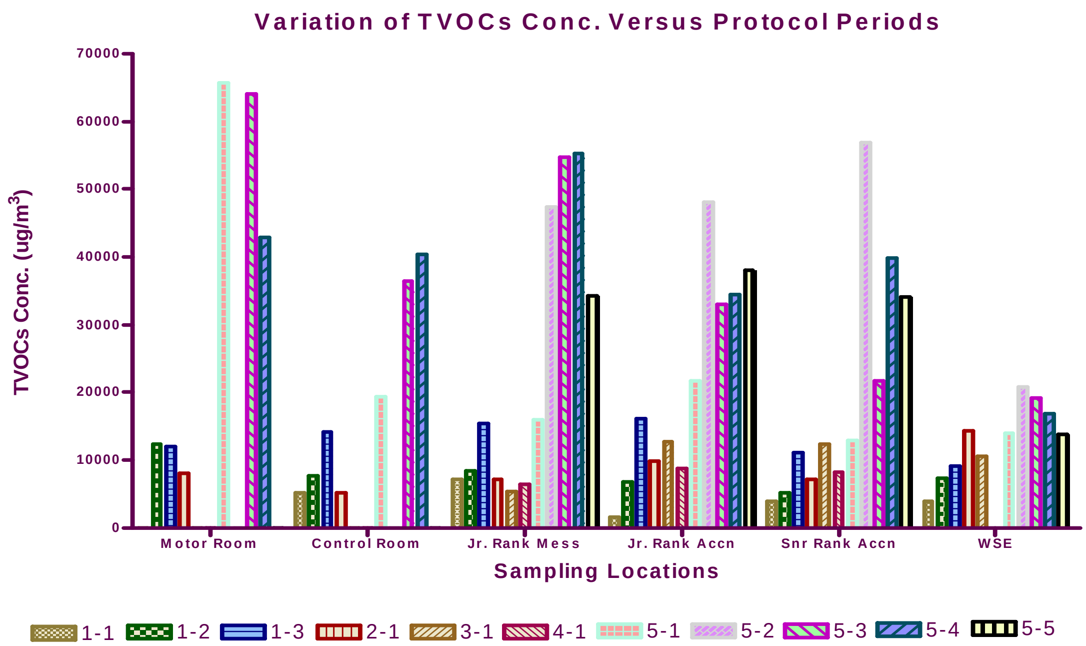

Figure 7. *Total Volatile Organic Compound (TVOCs) concentration variation for each collection period in each protocol within the six compartments of the submarine (TVOCs includes over 300 compounds consisting of aromatics, aliphatics and fluorocarbons).*

Findings also identified that the least affected area was the WSC (average concentration 16.8 mg/m^3), in which there were moderate increases in VOCs during and after the spill when compared with the other compartments. Although VOC contaminant levels were quite low and within limits, findings suggest this compartment has a pocketing effect that even with snorting, fresh air was not sufficient to clear the area of VOCs. This pocketing effect is exemplified in protocol two where the VOCs actually increased by 36% during snorting in the WSC (Figure 7, Sample 2-1), while the total VOCs dropped by 64% in the control room and 54% in the junior ranks mess during this short operational snort of 20 minutes.

In examination of the total concentrations of VOCs; the largest concentrations were seen during Protocol five (Figure 7). This could be presumed a result from the contributions of emissions from the engine backfire at the end of the snort during Protocol four, as other dived scenarios did not produce this increase of VOCs, and all other procedures and policies remained the same. From this event the greatest total concentration of VOCs was seen in the junior ranks mess, and was not what would have been expected (Figure 7). Furthermore, as the distribution pattern of contaminants has been shown to diffuse throughout the submarine, this selective increase requires further detailed analysis as the cause is not likely a result of contributions from engine emissions. The use of cleaning solvents is also not likely the cause of the selective increase in the junior ranks mess, as cleaning solvents are used throughout the submarine

From the detailed analysis of the specific VOCs present, d-limonene was identified in all samples during the study, with the largest concentration found in the junior ranks mess in protocol five (535 $\mu m/m^3$), twice that of any other compartment. d-Limonene belongs to the VOC class of terpenes, found in organic solvents that are usually derived from natural sources such as pine trees or citrus fruit. d-Limonene is also commonly used in many consumer products to give the lemon-like odour in polishes, cleaners, degreasers, and orange oil as an example [13]. Although levels of d-limonene were seen during all portions of the study, in comparison to the levels seen at the beginning of the trial it can be determined that d-limonene was generated onboard and was not part of the background emission from the boat itself. Further, the variation pattern of d-limonene levels have shown that at the beginning of Protocol five d-limonene levels were initially low but drastically increased in the junior ranks mess during the protocol and then dropped during the later portion of the protocol.

It is not sure where the limonene came from, but likely it has originated from some type of consumer cleaning product or from the presence within citrus fruits such as lemons or oranges. There are two possible explanations for the drastic increase in d-limonene levels in the junior ranks mess after the spill. The first one being that limonene was a trace additive in the motor oil or fuel, which is not very likely considering the largest increases were found in the junior ranks mess (Figure 8). The other likely explanation was that the crew might have tried to mask the odour with lemon-scented personal products or sprays, or its presence could have resulted from the preparation or consumption of citrus fruit. As the levels were highest in the junior ranks mess with a selective and substantial selective rise therein, the later is the most likely explanation for the increase.

To determine the exposure to the specific VOCs as well as to determine compliance with the current exposure guideline (BR 1326), an open characterization of the major VOCs was conducted using Mass Spectrometry. In this analysis an 80% match between chemicals detected and that contained within the library was selected. Applying this criterion, the top compounds were identified and a semi-quantitative approach was applied for these compounds, expressed as toluene or acetone equivalent (Table 2).

Table 2. *Fingerprint identification of the top contaminants during 18 hours dived under sonar quiet conditions after an engine backfire (TVOC levels represent the average total concentration from five samples taken during the 18-hour dived sonar quiet period for each of the compartments).*

Compound	**Motor Room (ug/m3)**	**Control Room (ug/m3)**	**Junior Ranks Accommodation (ug/m3)**	**Jr. Rank Mess (ug/m3)**	**Senior Ranks Accommodation (ug/m3)**	**WSC ug/m3)**
1-H Indene, octahydro	496	260	281	325	275	194
1H-Indene, octahydro-, trans- + Cyclohexane, 1,1,2,3-tetramethyl-	580	269	304	359	297	197
2,6-dimethyl decane	543	300	322	392	354	165
Benzene, 1,2,3-trimethyl-	764	428	452	507	239	270
Benzene, 1,2,4-trimethyl-	853	517	563	611	490	354
Benzene, 1,3,5-trimethyl-	1140	672	707	773	647	480
Benzene, 1-methyl-3-propyl-	760	405	421	489	401	241
Cyclohexane, propyl-	441	N.L.	238	132	344	168
Cyclopentasiloxane, decamethyl-	N.L.	636	724	955	691	360
Decane	1510	818	911	1160	851	429
Decane, 3-methyl-	511	139	N.L.	235	93	N.L.
Dodecane	793	331	359	458	349	181
Ethanol	1280	1190	1250	1740	1410	401
m/p-Xylene	740	508	610	650	530	253
m-Cymene	820	410	427	534	424	197
m-Ethyltoluene	997	571	617	671	566	340
m-Propyltoluene	754	499	434	435	365	244
Naphthalene, 1,2,3,4-tetrahydro-	862	279	332	387	327	145
Naphthalene, decahydro-	1050	554	573	680	551	333
Naphthalene, decahydro, 2-methyl-	731	400	363	460	355	176
Nonane	1940	1060	1250	1330	1060	579
Nonane, 2,3-dimethyl-	569	269	296	350	288	174
Octane	N.L.	279	289	337	258	151
o-Ethyltoluene	931	507	542	597	499	309
o-Xylene	418	281	329	338	285	185
Undecane	1380	749	783	1000	784	331
Total Average TVOCs	57800	31700	34700	41300	32900	16800

Almost all of the organic compounds were found to be diesel fuel aliphatic hydrocarbons or fractions from petroleum products used in fuels, solvents, and cleaners [13, 14, 15]. Levels of total VOCs were found to be within the limit identified by Standard, BR 1326, for total organics (40 mg/m^3) during routine patrol and snort conditions. However, when unexpected contributions of contaminants occur from spills or an event such as a backfire of an engine, as occurred during the final stages of the snort, contaminants are brought into the submarine. Although diesel fuel combustibles (CO_2 and CO) and key aromatics (BTEX) were within limits during all scenarios, in all compartments, the allowable limits for total organics were exceeded upon submergence after the engine backfire in all compartments, with the exception of the WSC. As seen in Table 2, the average contribution from each VOC is relatively small in Protocol 5, but together the total VOCs were exceeded. Results have shown that the average concentration in each compartment was 57.8 mg/m^3 in the motor room, 41.3 mg/m^3 in the junior ranks mess, 34.7 and 32.9 mg/m^3, respectively, in the junior rates and senior rates accommodation space, and 31.7 mg/m^3 in the control room and 16.8 mg/m^3 in the WSC. It would appear from these average concentrations that only the limits were exceeded in the motor room and junior ranks mess. However, as seen in Figure 7, there was a dispersion of total VOCs within the submarine over the 18-hour dived period. Four hours after the engine backfire; total VOC levels peaked to 56.6 mg/m^3 and 47.8 mg/m^3 in the senior and junior rates accommodation space, respectively. While not all samples could be analyzed from the control room, levels peaked at 40.1 mg/m^3. These findings are not a result from normal operating procedures, thus exceeding the standard would not be considered a normal occurrence. Even though contributions resulted from inadvertent events, this occurrence identifies that measures need to be taken to avert or mitigate rare and unexpected events that contribute to exposure.

Although the presence of VOCs is neither novel or uncommon, their presence suggests a continued longstanding exposure concern as components such as aromatic hydrocarbons are known to be irritants, they can produce narcotic effects at high concentrations, and may be carcinogenic [13, 14]. For this reason, and the fact that the contribution from the engine backfire was only known retrospectively, it is essential that a method to identify their presence be brought onboard. Their potential health effect would also justify that means should be taken, where possible, to reduce their presence to the lowest levels possible. A lengthier snorting time could have reduced VOC levels to within Standard limits, if the levels were known. However, exposure to VOCs and particulates could be reduced substantially by installing filters in the ventilation system. Ideally, such a filter would be a HEPA-filter (High Efficiency Particulate Arrestance) capable of filtering out particles as small as bacteria, an added benefit to reducing illnesses, should they occur.

It is not known however if introduction of a filtering capacity within the ventilation system is either reasonable or feasible, either from a mechanical perspective or from a housekeeping perspective. Nevertheless, a filtering capacity of any sort whether charcoal or HEPA would significantly reduce the presence of volatile compounds and particulates, and as such an investigation of its feasibility should be completed. It appears that a filtering medium, although limited, is present in the plenum space of the Victoria class. Expanding upon this existing capacity should be explored.

Variations in chlorinated compounds

A number of chlorinated compounds were also detected onboard the submarine. As identified in Table 3, these chlorinated compounds are used as refrigerants in air conditioners, refrigerators and chillers; ingredient in solvents, degreasers or adhesives; impurity in solvents, and, chloroform is also found in cigarette smoke [12]. All levels were well within the MPC for both the total halogenated compounds (5000 mg/m^3) and specific refrigerant limits (5000 mg/m^3) set within BR 1326.

Analysis has shown that the average total volatile chlorinated hydrocarbon concentration during the sonar quiet dived submergence was 165.2 ug/m^3 in the control room, 126.1 ug/m^3 in the motor room, 146.3 ug/m^3 and 129.8 ug/m^3 in the junior and senior rates accommodation space, respectively, and, 119.5 ug/m3 in both the junior ranks mess and the WSC. These results indicate that the control room contained relatively the highest levels of chlorinated compounds, although the levels were quite similar throughout the submarine. Trichloroethylene and tetrachloroethylene were the two top target chlorinated compounds found in all of the compartments during the sonar quiet dive conditions (Table 3). These findings would suggest that the largest contribution of chlorinated hydrocarbons resulted from the use of solvents [13], and that their presence diffused throughout the submarine. Although the chlorinated compounds were well within limits set within Standard, BR 1326, to reduce exposure to the lowest possible levels, measures should be taken to review the toxicity of all items taken or used onboard the submarine to reduce unnecessary exposure to potentially harmful compounds.

Table 3. *Average chlorinated hydrocarbon concentration and sources of atmosphere contamination during an extended 18.5 hour dive during sonar quiet conditions.*

Major Compounds	Source	Concentration
Dichlorodiflouromethane	Freon 12-refrigerants	2.0 $\mu g/m^3$
Chloromethane	Historical refrigerant, cigarette smoke	4.5 $\mu g/m^3$
Trichloromonoflouromethane	Freon 11- refrigerants	2.8 $\mu g/m^3$
Chloroform	Impurities in technical grade solvents	4.7 $\mu g/m^3$
Trichloroethylene	Degreaser, adhesives	66.9 $\mu g/m^3$
Tetrachloroethylene	Solvent, cleaning, degreaser	63.2 $\mu g/m^3$

Evaluation of onboard detection equipment

During this trial three potential air monitoring devices were also assessed for their accuracy in detecting the main atmospheric contaminants in a submarine, the asphyxiant gases CO_2, CO, Hydrogen (H_2) gas and Nitrogen Dioxide (NO_2) that displace O_2, and as well, monitoring for O_2 concentration. Both the portable Draeger Mini-warn multi-gas monitor and the Draeger X-am

7000 monitored for CO_2, CO, H_2 and NO_2, with the X-am 7000 additionally monitoring for O_2. While the Analox Sub MKIP Hyperbaric Atmosphere monitor measured for CO_2 and CO only. The submariner community selected these instruments as potential replacements for the current method of detecting contaminants, gas detector tubes.

The requirement to replace the current method of detecting and quantifying contaminants (Draeger tube) has been considered necessary as the detector tube method is known to have an inherent error of ± 25%, and measurements are prone to further error from interfering contaminants and conditions (i.e., temperature, pressure and relative humidity, and human error) [3]. Therefore, the current method of detecting gases requires replacement as it is unreliable, expensive and inaccurate.

Reliability and accuracy of the replacement monitoring instrumentation were compared to the DRDC study instrumentation for O_2, CO_2, and CO, and confirmation of detection and quantification of the atmospheric gases from the DRDC instrumentation was assured with known calibration gases. Further, when discrepancies between DRDC instrumentation and portable replacement instrumentation were noted, recalibration was performed on DRDC equipment to assure accuracy. No restrictions or interferences were imposed on the monitoring of air quality with the replacement instrumentation; thus, submarine routine practices and procedures were adhered for atmosphere monitoring of contaminants.

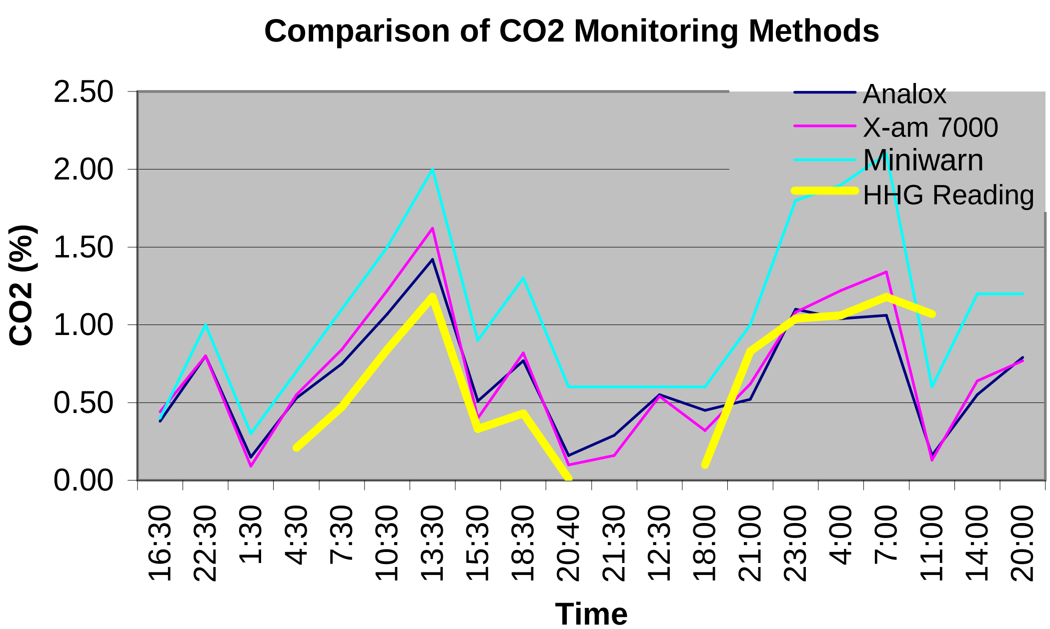

Figure 8. *Comparison of CO_2 readings between study detection equipment and potential replacement monitors during the three day habitability trial (data includes CO_2 readings during all five protocols, monitoring dived and snort protocols. Replacement monitors also monitored during non-study periods as part of standard operating procedures).*

Findings have shown that there was a significant disparity between the instrumentation readings used in the habitability trial from DRDC to detect O_2, CO_2, and CO, and the potential replacement monitors. The trend rise and fall of contaminants was inline with the DRDC instrumentation, as seen in the CO_2 levels identified in Figure 8; although the CO_2 concentration varied from 0.3 % (Analox) to almost a full 1% (Mini-warn) difference between the DRDC study instrument and those potential replacement instruments used within the submarine. This translates to a 3000 ppm to 10,000 ppm variance from the actual concentration within the submarine, which can be considered significant as the identified level of CO_2 from instrumentation readings are intended to provide the atmospheric state of the submarine and the need for purification measures. Although the portable replacement instrumentation suggests misleading increases in CO_2, there is no additional health risk imposed. However, the false amplified readings would result in early activation of an already short supply of CO_2 canisters than necessary.

The same degree of disparity in readings was also found in O_2 measurements with all of the portable instrumentation. While the discrepancy in measurement of CO levels in both the Mini-warn and the X-am 7000 was found to be the most extreme, at 3 to 8 times greater than actual concentrations. Both instruments read 40 ppm higher levels of CO under patrol conditions to 80-90 ppm higher CO levels under sonar quiet conditions than those identified with DRDC instrumentation. As CO is a product of fuel combustion and there were only two periods where combustion occurred (snorting with engines running), the significant CO levels identified by the instrumentation, especially during the extended dive, is not likely. In comparative trials in the Oberon class, the levels of CO did not reach 50 –100 ppm [3, 6], and previous trials with this class of submarines when owned by the RN did not see CO at this level [5].

This inaccuracy with the instruments detection of CO and O_2 can, in part, be explained by the detection method of the instrumentation, which uses electrochemical cells that once activated cause a continuous reaction. This detection method is known to have an increased error in detection with time, and thus the manufacturer suggests the need for increased calibration. There is also an inherent problem with electrochemical cells in measuring CO levels, as the CO sensor does not compensate for hydrogen and there is a cross sensitivity, thus potentially giving false readings. These types of cells are also consumable and have a life span. Manufacturer testing has identified that use in a normal, oxygen stable environment with no undue harsh conditions (i.e., pressure changes, interfering chemicals, humidity, and temperature fluctuations), cells should be replaced after one year. The manufacturer has also indicated that an oxygen sensor is not guaranteed to perform well for more than two months. Therefore, use of this detection method under conditions beyond that guaranteed by the manufacturer requires routine calibration to ensure accuracy and cell detection reliability. As such, conditions within the submarine might reduce the suggested lifespan of the cell. Sensors of this type should therefore be calibrated off shore prior to use, to assure a clean air source and confirmation of accuracy, and testing should be done with known concentration of gases to verify detection accuracy once under sail.

The detection method for measuring CO_2 by DRDC and the replacement instrumentation was by IR technology, a measurement capability that identifies contaminants by the absorption at a specific wavelength. The set point wavelength is specific for a compound and therefore significantly reduces the risk of false readings due to interferences. It is considered a very reliable method of detection, and considered the method of choice when allowable. Thus, as all of the equipment for CO_2 monitoring used an accurate and reliable detection technology the increased CO_2 readings from the assessed instrumentation would not likely be due to equipment failure. As

DRDC instrumentation accuracy was confirmed with known calibration gases, this would suggest that the inaccuracies of the assessed instrumentation readings were likely also a result of human error in data collection. The provision of detailed operating procedures would significantly aid in overcoming error as a result of misuse of equipment.

There are many considerations that need to be taken into account when choosing a monitor to detect the contaminants of concern within a submarine. The harsh conditions within the submarine (i.e., temperature fluctuations, humidity, pressure changes and a mixture of interfering contaminants) do not lend themselves to simply choosing instrumentation that has been produced for an industrial setting as detection instrumentation may not function well in this platform [3], but as well, there are other considerations that need to be met. For the submarine platform the size of instrumentation is an issue as storage and placement needs to be considered. As well, power supply, ease of use, requirements for use such as calibration, and ongoing maintenance while at sea or ashore also need to be considered. The choice in instrumentation then becomes much more difficult and limited. Consideration should be given to choosing a method that is the most reliable, accurate, and user friendly, if possible. Infrared detection is considered the method of choice for detection of CO_2 and CO as the wavelength for detection is unique, and thus there is no risk of false reading from interfering contaminants. Infrared technology also can measure organic compounds (i.e., VOCs) although the band width may not be selective to the specific compound.

Thus, although significant inaccuracies were found with all of the potential replacement instrumentation, an understanding of the limitations of the detection technology would certainly assist in ensuring accurate and reliable monitoring of atmosphere gases. Of the three instruments, the Analox was only capable, or set-up, to monitor for CO_2 and O_2. If an instrument is chosen to monitor for acute gases, instrumentation should be chosen to monitor for all of the atmospheric gases that are of concern and require monitoring. It is also suggested when choosing a monitoring capability that the same type of instrumentation should be purchased for all types of monitoring requirements, to include routine, charging alongside and damage control, where possible, as this would reduce the likelihood of error that could result from interchanging equipment with different operating requirements.

Although different technologies are present that would meet the needs of the submarine platform, and perhaps perform better and more reliably, findings from this study indicate that the Draeger X-am 7000 and the Mini-warn could be considered an effective replacement to Draeger tubes if the shortcomings are addressed. To ensure greater and consistent reliability and accuracy, dedicated calibration of the instrumentation is required and detailed operating procedures are needed, to include a maintenance program for electrochemical cell management. The Mini-warn has in fact been extensively tested by the US Navy, and this instrument has been distributed and is used on US submarines.

Recommendations

The following recommendations are made, based upon the findings from this study and taking into consideration the operational requirements of the submarine platform.

1. Purification efficiency

    a. Findings have confirmed and are in agreement with the Standard, BR 1326, that a 35-minute snort can effectively clear the submarine to ambient air conditions, as long as the contribution of contaminants is sufficiently small. Findings have further shown that the contribution of contaminants can alter the time required to effectively clear the submarine, as seen in the inadvertent engine backfire and the contribution of both combustible and non-combustible gases. Additionally, a 35-minute snort prior to charging the (Built-in-Breathing System) BIBS and Emergency Breathing System (EBS) systems from air within the submarine can also solve the current difficulties in meeting the compressed breathing air standards. However, to ensure ambient air conditions have been achieved, contaminant levels should be monitored; measuring of CO2 levels as a minimum indicator of atmospheric conditions from snorting should be considered.

    b. Study findings have also shown that two canisters activated fore and aft, under the conditions and period of time studied, will effectively slow the rise of CO2 levels and maintain CO2 concentrations within the limits set by Standard, BR 1326.

2. Improvements to atmosphere circulation and habitability

    a. Study findings have shown a pocketing effect in the WSC. Although the accumulation of contaminants was not significantly greater than any other compartment, results identified that a 20-minute operational snort was not effective in clearing the compartment. Findings identified that a snort was not effective in diluting the concentration of total VOCs, and instead there was an increase of 36% after the snort in the WSC. Further, although there was a decrease of contaminants in the non-commissioned members' accommodation spaces (40% and 36% in the junior and senior rates space, respectively), the reduction of total VOCs was not as great as that seen in the control room and junior ranks mess (64% and 54%, respectively). Thus, to improve circulation of air within the WSC and accommodations spaces it is suggested that a fan be placed in these areas to prevent pocketing and assist in removal of contaminants during snorting.

    b. Knowing that there are considerable particulates and volatile compounds present onboard the submarine, it would be prudent to investigate the possibility of placing a filtering capacity in the ventilation system of the submarine to reduce contaminants prior to circulating air throughout the boat. In discussion with operators, it is believed that the plenum space in this class has a limited filtering lining, but with the addition of an activated charcoal filter or a HEPA filter, both particulates and VOCs could be significantly reduced. The better option would be a HEPA filter as it would also eliminate bacteria, thus reducing the spread of illness when present onboard. It is recommended that an engineering feasibility study be carried out to investigate the possibility and practicality of installing these filters.

c. Although CO_2 levels were kept within the limits identified in the Standard, BR 1326, the placement of the CDAUs is not ideal to effectively remove CO_2 equally and in all compartments of the submarine, especially in the lower deck. Methods should be sought to investigate more efficient methods of removal of CO_2 than the soda-lime canisters and improving the ventilation mechanics of the CDAUs. Alternate and potentially more effective methods of absorbing CO_2 should be explored, such as the research undertaken by the Experimental Diving Unit at DRDC Toronto in assessing the potential of Lithium Hydroxide absorbing blankets in CO_2 removal.

3. Air quality monitoring and management

a. To ensure the atmosphere within the submarine remains within the limits set within the Standard, BR 1326, a method to accurately and reliably detect contaminants is required. The current method of detecting and quantifying contaminants (Draeger tubes) has been found to be inaccurate, expensive and unreliable. Thus, commercially available monitoring capability instrumentation should operate reliably and accurately in the unique and harsh conditions of the environment, but as well, it must also take into consideration ease of use, size, power supply and operating and maintenance requirements. Consideration should also be given to using the same type of instrumentation for all monitoring conditions, as this would reduce the likelihood of error that could result from interchanging equipment with different operating requirements (i.e., routine, charging along side, and post-emergency).

In assessing the potential replacement monitoring systems significant inaccuracies were found with all three instruments. However, with the introduction of dedicated and ongoing calibration and the provision of detailed operating procedures, to include a maintenance program for electrochemical cell management, the Draeger X-am 7000 and the Mini-warn could be considered an effective replacement to Draeger tubes.

b. The Department of National Defence has continued to devolve the responsibility of procurement of supplies to the unit level. This has resulted in local purchases of materials for submarines (i.e., solvents, cleaning agents, etc). Although control measures have been taken to control products that are brought onboard, further control measures should be taken to reduce unnecessary exposure of the crew to potentially harmful compounds and collate the material. This can be achieved by using the Royal Navy's BR 1326 (A), *Material Toxicity Guide* [16], ensuring the latest addition is available, and expanding on the guideline, as needed. Collaboration with the RN on this document will also reduce efforts and ensure distribution of knowledge of potentially toxic materials. This would result in the introduction of a common guide that would enhance the awareness amongst end-users, managers and policy advisors.

c. The current Standard, BR 1326, was developed to provide guidance for air purification within submarines for the RN, to include the Victoria class submarine, previously known as the Upholder class. As such, the guidance given for use of air purification equipment was developed for the RN based on the number of expected crewmembers onboard. The guideline thus provides an indication of the time to reach critical concentrations of CO_2 and O_2 for 30, 40 and 50 crewmembers, which does not include the number of personnel Canada intends to employ on the submarine. Further, BR 1326 does not provide guidance as to when activation should occur. This simply points out that the interpretation and application of the Standard ultimately governs the composition of the atmosphere. As there is no canister or candle replacement schedule and no formula to accurately predict replacement, the weak link is the interpretation of the Standard and the risk of miscalculation when relying on inaccurate and unreliable methods of measurement.

With no current guidelines for scheduling or available calculations to predict accurate scheduling of canisters or candles, crews must rely on inaccurate measures, past experiences, or memory. It would be helpful to operators if a reliable, consistent and accurate guideline were available so that fully informed decisions could be made when operational situations dictate snorting is undesirable or impractical.

The provision of an operating curve for this class of submarine which provides a timeline for the degradation of the environment (for CO_2 and O_2) and the effectiveness of air purification measures to include snorting (based on initial concentration and ventilation) and CO_2 scrubbing and O_2 generation would be helpful in managing air quality onboard the submarine. These guidelines are not currently available in BR 1326.

4. Future Study

It is unfortunate that O_2 candles were not activated during this study as the O_2 levels were thought to be within specifications and activation was not necessary to maintain atmospheric conditions. Instrument error was subsequently found to be the problem. As identified in previous habitability trials, instrument difficulties are not uncommon [3, 5, 6]. Thus, to further aid in the selection of future monitoring instrumentation, determine the efficiency of the O_2 candles, and develop a degradation and elimination curve of the atmosphere for a Canadian crew complement, an additional study should be performed using potential replacement instrumentation, with a backup capability to assure results are obtained. Further, conditions in this study did not allow the time to reach maximum levels of contaminants to be determined. Ideally, a study that monitored air quality under operational configurations that produced a worse-case atmospheric condition would provide the results needed to guide the Navy in maintaining atmospheric quality onboard the submarine. An additional study would also assist in achieving the broader habitability objectives: to development an atmospheric monitoring policy; provide evidence of the effects of smoking; and assist with the development of air purification procedures for smoke clearance and other emergencies.

References

1. Air Purification in Submarines. Royal Navy Standard BR1236, 1990.
2. Submarine Air Quality Management Initiatives. File 10081-1 (NOO Comd.), 26 January 1998.
3. An Air Quality Assessment Onboard an Oberon Class Submarine: HMCS Okanagan. DCIEM Technical Report, TR 2000-105.
4. NIOSH Manual of Analytical Methods. 4th Edition. U.S. Department of Health and Human Services. National Institute for Occupational Safety and Health, Cincinnati, Ohio, 1994.
5. Sea Acceptance Test, Air Purification Test Form for Conventional Submarines- HMS Unseen. RN-SSCF72, 1992.
6. An Air Quality Assessment Onboard an 'Oberon" Class Submarine- HMCS Okanagan. DCIEM Report No. 87-RR-28, 1987.
7. Effects of Severe Heat Stress on Respiration and Metabolic Rate in Resting Man. Saxton, C., Aviat Space Environ Med. 1981; May, 52 (5) 281-286.
8. A Study of Atmosphere Control in Patrol Submarines in the Royal Navy. W. Nimmo-Scott. Report to Flag Officer, Submarines, 1981
9. Comparative Oxygen Guide: Paramagnetic Sensors. http://www.delta-f.com/O2Guide/O2GuidePara.html
10. Department of Defence. Mil-Hdbk 759 C. Handbook for Human Engineering Design Guidelines. 31 July 1995
11. American Conference of Governmental Industrial Hygienists – Threshold Limit Values and Biological Exposure Indices. ACGIH, Cincinnati, Ohio, 2004
12. Internal Submarine Environment. Mazurek, W., Gan, T.H., Hanhela, P.J. Fifth International Workshop on Submarine Air Monitoring and Purification (SAMAP 2005), Uncasville, USA
13. Clinical Toxicology of Commercial Products. 5th Edition. Williams and Wilkins, Baltimore & London, 1984.
14. American Conference of Governmental Industrial Hygienists- Documentation of the Threshold Limit Values and Biological Indices. ACGIH, Cincinnati, Ohio, 2004.
15. Submarine Health Risk Protection Program: Identification and Evaluation of Chemical and Biological Health Risks to Submarine Personnel. DRDC Toronto Contract report, November 2003.
16. Materials Toxicity Guide. Royal Navy Standard BR 1326 (A), 1990.

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
BIBS	Built-in-Breathing System
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
CDAUs	Carbon Dioxide Absorption Units
CF	Canadian Forces
CO_2	Carbon Dioxide
CO	Carbon Monoxide
COHb	Carboxyhemoglobin
DND	Department of National Defence
DPM	diesel particulate matter
DRDC	Defence Research and Development
EBS	Emergency Breathing System
HEPA	High Efficiency Particulate Arrestance
HHG	Health Hazards Group
IR	Infrared
MARLANT	Maritime Forces Atlantic
MAROPGRU5	Maritime Operations Group 5
MPCs	Maximum Permissible Concentrations
N_2	Nitrogen
O_2	Oxygen
ppm	parts per million
r^2	regression coefficient
RAN	Royal Australian Navy

RH	Relative Humidity
RN	Royal Navy
SOPs	Standard Operating Procedures
TD	Thermal Desorption
TWA/TLV	Time Weighted Average-Threshold Limit Value
TVOCs	Total Volatile Organic Compounds
TWA	Time Weighted Average
VOCs	Volatile Organic Compounds
WSC	Weapon’s Storage Compartment

DOCUMENT CONTROL DATA
(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document, Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's document, or tasking agency, are entered in section 8.) Publishing: DRDC Toronto Performing: DRDC Toronto Monitoring: Contracting:	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

A Baseline Air Quality Assessment onboard a Victoria Class Submarine − HMCS Windsor (U)
Une étude de référence sur la qualité de l'air abord des sous−marins de classe Victoria − HMCS Windsor

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Yvonne D. Severs

5. DATE OF PUBLICATION (Month and year of publication of document.) May 2006	6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 43	6b. NO. OF REFS (Total cited in document.) 16

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Report

8. SPONSORING ACTIVITY (The names of the department project office or laboratory sponsoring the research and development − include address.)

Sponsoring:
Tasking:

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document) DRDC Toronto TR 2006−087	10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (Any limitations on the dissemination of the document, other than those imposed by security classification.)

Unlimited distribution

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11), However, when further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited announcement

DOCUMENT CONTROL DATA

(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

(U) In 1998, as part of the management plan for the purchase of the Royal Navy (RN) Upholder Class Submarines (subsequently designated Victoria class), initiatives for submarine air quality was identified. This air quality study is a continuation of this plan; with the objective to obtain information to assist in confirming the status of the submarines and what future air quality management was necessary. This trial thus represents a baseline habitability evaluation of Canada’s Victoria class submarines to confirm compliance with the current maximum permissible contaminant limits stipulated in the Air Purification Standard, BR 1326, and how that can best be achieved. To achieve this aim the study monitored the effects of: air purification capabilities (management of Oxygen (O2) and Carbon Dioxide (CO2)); routine housekeeping procedures (cleaning and cooking); lifestyle effects (smoking); system effects (engine, compressor and motor); and the effectiveness of snorting, the resulting air exchange and the reliability of monitoring instruments. Monitoring the atmospheric conditions has shown that under normal routine operational conditions, following standard operating practices and procedures, all contaminants found in the atmosphere were within limits set in BR 1326. However, when there are unexpected contributions of contaminants, such as the intake of engine backfire emissions, combustible by−products and key aromatics (i.e., Benzene, Toluene, Ethylbenzene and Xylenes) remain within limits, but the total allowable organics limit is exceeded (40 mg/m3). Thus, under normal operations contaminant levels are within maximum permissible limits. Findings would therefore indicate that exceeding the standard is not considered a routine occurrence and can be attributed to the engine backfire that occurred while snorting. Maintaining contaminants within specifications when dived are difficult at best, but more so when non−routine events occur that unexpectedly contribute an unknown quantity of contaminants. This can be attributed to many factors; air purification measures are minimal (CO2 and O2 only), poorly placed and antiquated, and there is a lack of exhaust ventilation. Further, there is poor to non−existent air exchange compounded by compartmentalization, pocketing in the WSC, and current contaminant measurement devices have been shown to be prone to measurement errors. There is also a lack of guidance for the degradation timeline of the atmosphere, replacement schedules for CO2 canisters and O2 candles, and no formula to accurately predict replacement. Therefore, guidelines to assist in maintaining air quality are open to interpretation. Although atmospheric conditions were found to be within specifications during routine operations, to successfully manage submarine air quality, ensure the health and safety of the submariner, and support the conduct of efficient operations, especially during unexpected contributing events, we need to look beyond compliance with regulations. Continued research is necessary to enlighten everyone involved, to guide development of submarine atmospheric policy and procedures and future instrument selection, and to validate the feasibility of atmosphere improvement through engineering changes. As well, improved habitability requires a CO2 canister replacement efficiency review with associated replacement schedules provided, and a toxicological review of all items intended for use onboard prior to purchase, with a general record maintained in a materials toxicity guide. An ongoing review and operational platform testing of adequate technologies for the accurate and reliable monitoring of contaminants under the harsh conditions of the submarine is also necessary.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) Air quality; assessment; submarine; Victoria Class; VOCs; volatile organic compounds; diesel exhaust; solvents

Defence R&D Canada

Canada's Leader in Defence
and National Security
Science and Technology

R & D pour la défense Canada

Chef de file au Canada en matière
de science et de technologie pour
la défense et la sécurité nationale

DEFENCE DÉFENSE

www.drdc-rddc.gc.ca