Automated control of breathing air cylinder charging

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SYNOPSIS

With modern trends toward lean manned warships the ability to achieve effective damage control and fire fighting depends upon a number of key parameters. One of these parameters is to deliver the correct number of charged breathing air sets to attack and support parties when required. Investigations by the Marine Auxiliary Systems (MXS) IPT have uncovered some concerns over the methodology of the charging process and the quality of the air that is delivered. These concerns fall into four main areas: Over/Under Charging of cylinders, Effects on cylinder life, Quality of charging air, Effects on operability. The purpose of this paper is to introduce and discuss the elements that affect the charging process with particular attention to instantaneous flow rates and their effect on filtration. The paper then addresses the effect of charging profile on the speed of fill and the ultimate final mass charge of available breathing air within the cylinder. A developed solution to overcome the above problems is then discussed focusing on: Maximising air mass, Removal of human error, Better control of air quality, Reduced charging times, Extended cylinder life. An overview of the trials programme in HMS Excellent, HMS Ocean and the integration of the developed designs into the Type 45 destroyer will also be discussed.

INTRODUCTION

On a modern warship the ability to complete effective damage control and fire-fighting effort depends on a number of related factors. One of these parameters is the ability to deliver the required number of fully charged breathing air (BA) sets to the attack and support parties at the required times. Common practise, on the initiation of a fire situation, is to establish spare BA cylinder dumps of charged cylinders ready for use adjacent to the muster points of the attack and support parties. This practice allows for the used cylinders to be replaced on the BA sets when parties exit from the situation thus allowing the BA sets to be used by the next team to enter. Used cylinders being taken to the charging panel and re-charged from the ships High Pressure (HP) air system.

It has long been understood that the act of charging cylinders with HP gas has the potential to cause an increased safety risk to the charger and therefore this process is governed by strict safety procedures and operating codes.

BACKGROUND

As a result of the modern trend towards leaner manned ships, there is a potential increase in the number of “non-technical” users of the HP BA charging panels. With this in mind, the Marine Auxiliary Systems (MXS) Integrated Project Team (IPT) initiated a review of current practices and the methods by which cylinder charging takes place. The results from this review uncovered a number of issues, which are discussed in this paper.

The review highlighted a number of concerns over the methodology of the charging process, both from an equipment and operators perspective. The quality and quantity of the breathing air, delivered into the cylinders under charge, from the system was examined and the results compared to the breathing air quality standard, DefStan 68-284.

The nature of these concerns fell into four main categories:

i. Over/Under Charging of cylinders
ii. Effects on cylinder life
iii. Quality of charging air
iv. Effects on operability

DISCUSSION

There are a number of factors that govern a BA air cylinder charging systems' ability to deliver fully charged cylinders to fulfil the requirements of attack and support parties. These can all be derived from the filling philosophy of the system design.

Present systems rely on manually controlled charging, where ship staff are required to meter high pressure breathing air through a manual stop valve to control the rate of pressure increase within the BA cylinder. A typical schematic for this type of system is shown in Fig I below.

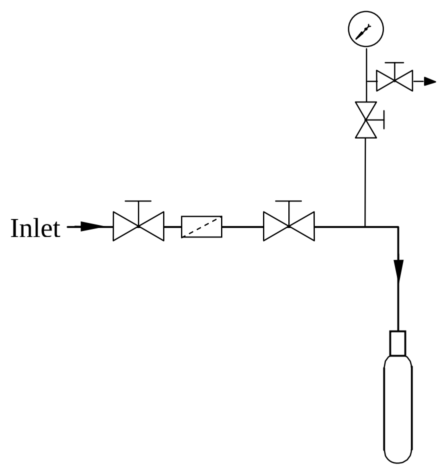

Fig I Typical schematic for manual filling system

There is a governing minimum fill time of 13 minutes attached to this method of manual charging. This method has however been proven to be impossible to adhere to in practise due to the required high level of control required on the manual stop valve.

Practical simulation of a controlled 13 minute linear fill has given a datum figure for the mass of breathing air required to determine that a charge has been successfully completed. This was achieved using an instrumented cylinder and a predetermined fill profile as shown in Fig. II below:

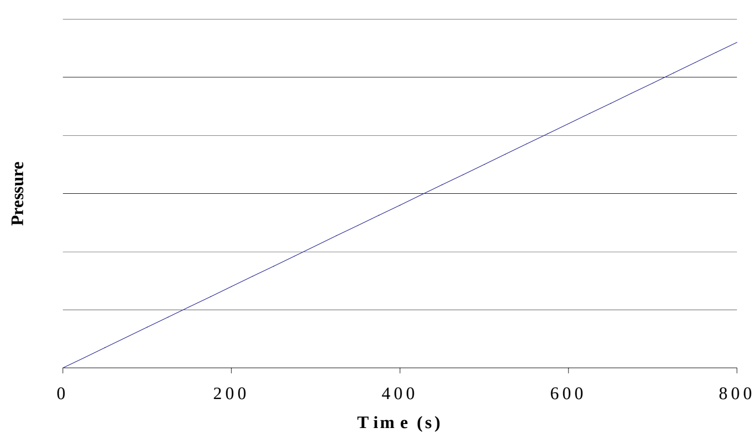

Fig II Linear 13 minute fill profile

The currently used manual filling philosophy leads to a wide number of potentially rapid fill profiles which will induce detrimental effects on the ability of the system to deliver fully charged cylinders as required. This is linked to the poor repeatability of the system and is determined by the amount of control that each operator applies to the manual stop valve. This human variable leads to a wide range of charging results in terms of fill profile, fill time and hence final outcome.

The least desirable fill profile results from the operator opening the manual control valve fully at the start of the fill in an attempt to charge the cylinder in the shortest period of time possible. The fill profile under this form of operation is shown in Fig. III below and follows the form of a fast exponential curve.

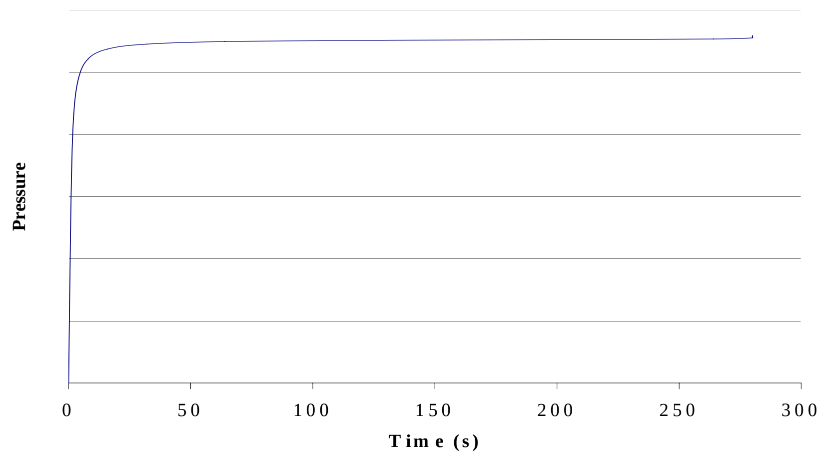

Fig III Fast exponential fill profile

Operation of the charging system in this way has a number of severe results on the final charged content of the cylinder.

The primary result of this fill profile is that the required pressure will be achieved within the cylinder but the air charged will be at a significantly elevated temperature. This equates to only a partial fill due to the cylinder pressure decreasing as the heat dissipates through the cylinder walls. As ambient temperature of the charged air is achieved, the pressure in the cylinder will drop well below the maximum fill value required. With the increased use of composite cylinders, where heat dissipation through the cylinder wall is slower due to the greater insulation properties of the material, this partial fill will take longer to detect.

It is in fact more useful to discuss fill completion in terms of mass of gas, as this variable is independent of temperature. Empirical data has shown that the charged mass of gas is decreased by some 15% using the fast exponential fill profile compared to the datum figure achieved whilst performing the 13-minute linear fill.

A second significant result is that, with a nominally empty cylinder attached to the charging panel, the instantaneous flow rate through the system is higher than the maximum allowable flow rate of the point of use filtration unit. This instantly compromises the quality of the breathing air in the cylinder and potentially contaminates the filling system itself for all remaining fills undertaken prior to maintenance of the unit. Any cylinders charged with the system in this condition would potentially retain these contaminants until they were cleaned prior to their next periodic inspection and revalidation cycle.

The final result of this fill profile is the possibility of overstressing the cylinder due to the elevated temperature and fast initial phase of the fill. Both these parameters have a long term detrimental effect on cylinder life.

A solution has been developed to overcome the potential issues discussed which pertain to the current manually controlled filling method This solution uses fully automated process control to facilitate programming and optimisation of the fill profile, integrated with the ability to action events at relevant points during a fill cycle.
At the centre of this solution is a closed loop control system, which is set around a high-pressure regulator. This control system uses proportional, integral and derivative (P, I and D) terms on an error feedback signal from the process pressure transducer, which is monitoring the cylinder pressure at all times.

A typical schematic for this solution is shown below in Fig. IV.

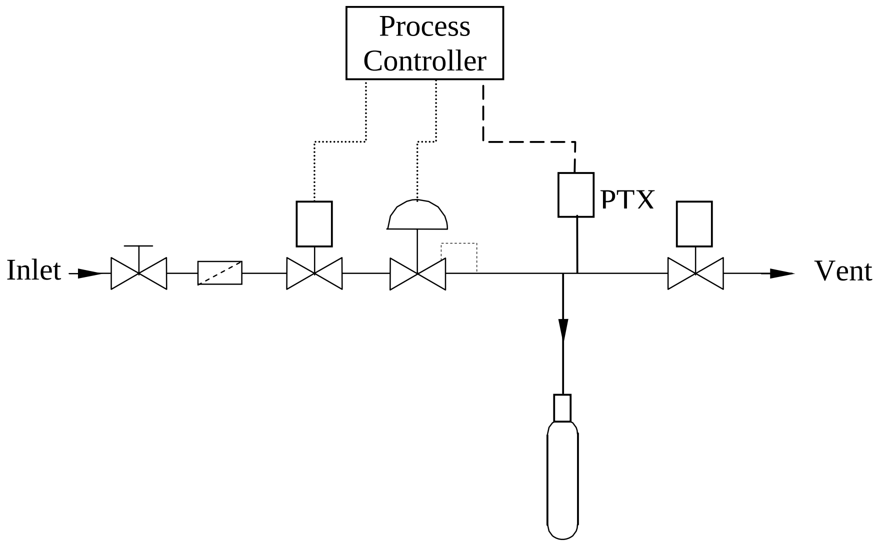

Fig IV Typical schematic for automated filling system

An optimised fill profile using a slow exponential form was determined by integrating a number of known operational as well as theoretical factors. An example of the fill profile form is shown in Fig V below:

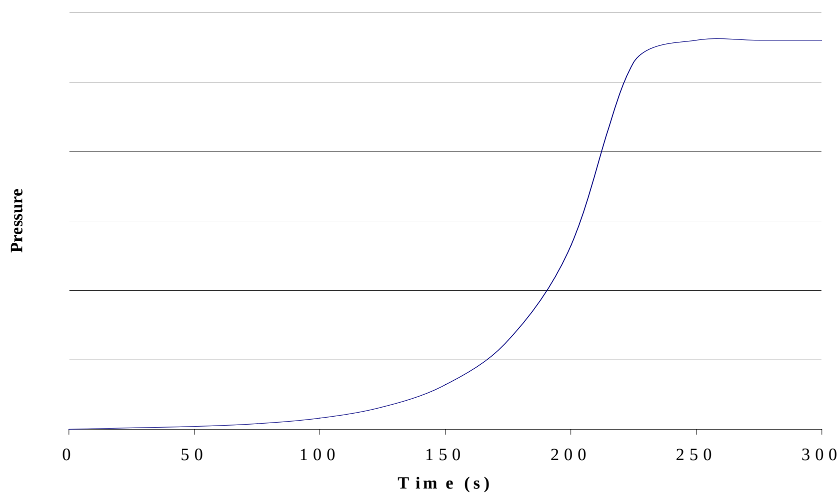

Fig V Slow exponential 5 minute fill profile

This profile form was initially selected by utilising the principles of the ideal gas laws shown in Equations (I) and (II):

$$PV = mRT \qquad \text{(I)}$$

For two given instances during a fill:

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2} \qquad \text{(II)}$$

Therefore for a constant volume, the pressure increase is proportional to the increase in temperature.

The slow exponential fill profile utilises a very gradual initial rate of pressure increase. This allows time for the temperature in the cylinder to dissipate through the cylinder wall, prior to further pressurisation and therefore temperature increase. This is intended to keep the overall temperature increase during the fill to a minimum. By minimising the temperature increase during filling, the mass of breathing air charged in the cylinder is maximised.

Further consideration was given to this profile to determine the minimum allowable filling time to achieve the throughput requirements, whilst ensuring that the control system did not at any point demand a flow greater than that of the point of use filtration system.

Final optimisation of this profile was undertaken through empirical testing on an instrumented prototype system to ensure all parameters were met. This method of deriving an optimised fill profile can be applied to any cylinder requiring charging and this can be performed through a large range of pressures and volumes.

Once optimised, this fill profile was integrated into the process controller and the resulting filling system offers the solution to the issues raised by the current manual filling method.

The optimised slow exponential profile gives an empty to fully charged cylinder in 5 minutes and this was shown empirically to deliver the required charged mass of breathing air as derived from the 13 minute linear fill result.

This fill period compares favourably with the 13 minute governing fill time previously dictated. The system, by also sensing cylinder residual pressure prior to filling, initiates the charge from the relevant point in the profile. This further reduces filling time in an emergency situation.

Acoustic emission testing and strain gauging was undertaken, on the cylinder, during a slow exponential fill to determine if any overstressing of the cylinders occurred with this reduced fill time. The results of this testing proved that there were no undue stresses applied to the cylinder. This leads to a system advantage that repeatable controlled filling using the optimised profile will increase the cylinder life as no potential overstressing can occur.

A further advantage of this system is that the charged breathing air quality is maintained for the life of the filtration unit due to the profile ensuring that no instantaneous flow rates occur above the maximum capability flow rate of the point of use filtration.

These advantages and solutions are a direct result of deskilling the operation of charging breathing air cylinders. This is achieved by reducing the operator input during charging to a two-button operation.

Once the cylinders are attached and the cylinder valves are opened, a start button initiates the fill cycle on the pre-determined fill profile. The system automatically performs all of the required elements of the fill procedure, following the optimised fill profile to its conclusion and then isolates the supply at completion.

Visual indication is used to alert the operator that the fill is complete. The operator then closes the cylinder valves and presses the vent button. This exhausts the filling line pressure and the unit resets to a standby state in readiness for the next fill. The fully charged cylinders can now be disconnected and used as required.

This deskilling means that there is no operator interaction with the control elements of the fill; therefore rapid uncontrolled charging is impossible.

A further benefit of the developed solution, allows for multiple cylinders to be charged simultaneously. Therefore it is possible using the slow exponential fill profile to charge all the cylinders of a five-man attack party in five minutes. The only limiting factor is the delivery capacity of the HP ring main.

This capability allows the spent cylinders to re-charged and ready for use in approximately 8% of the time needed under the currently use manual fill charging panel. This speed of turn round potential reduces the number of spare cylinders needed to support operations whilst ensuring that each member of the party enters the incident with the same mass of available air.

QUALITY OF BA CHARGING AIR

As highlighted earlier potential exists with the current manual fill system for the instantaneous flow rate through the system to exceed the maximum allowable flow rate of the point of use filtration. This instantly compromises the quality of the breathing air in the cylinder and contaminates the filling system itself for all remaining fills undertaken prior to maintenance of the unit.

The current BA testing regime involves the charging of an Extended Duration Breathing Air (EDBA) cylinder to approximately 60 Bar from the manual fill system. The cylinder is then sent to an approved laboratory for analysis of the contained air. The air content is analysed and compared against the requirements of Def-Stan 68-284[1] shown in Table 1. If the comparison is within the threshold limits a clean air certificate for that particular charging panel is issued and is valid for 6 months. The main issue with this type of test regime is that the results are only valid for the time and day that the particular cylinder was charged i.e. “Good on day of test”. In addition testing of air in this manner is both expensive and time consuming.

Table I: Test requirements and limits for compressed natural breathing air - Def-Stan 68-284

Test	*Property*	*Units*	*Limits*	*Comments*
1	Odour	Subjective	See NOTE 1	-
2	Free Water	Subjective	Nil	Visual examination of the delivered air
3	Water Content (H_2O)	Dew Point (^oC)	See Annex 1	See NOTE 2
4	Carbon Monoxide (CO)	ppm(v)	10 maximum	See NOTE 2
5	Carbon Dioxide (CO_2)	ppm(v)	500 maximum	See NOTE 2
6	Oil Mist	mg/m^3	0.5 maximum	See NOTE 2
7	Nitrogen	%(v)	Remainder	See NOTE 3
8	Oxygen	%(v)	21 ± 1	See NOTE 2
9	Other non-toxic gases	%(v)	< 1.0	See NOTE 2

NOTE 1 Free from odour that may have an adverse effect on the user or breathing apparatus.
NOTE 2 Maximum permissible level of contaminants at 15^oC, 101 kPa (1013 mbar)
NOTE 3 Includes argon, neon and other rare gases: no requirement for testing

Table II: Moisture content of compressed natural breathing air - DefStan 68-284[1]

Use	*End Usage*	*Supply Pressure (Bar)*	*Units*	*Limits (Maximum)*
1	(a) Air supplied in cylinders for diving and marine life support,	40 – 200	Dew Point (^oC)	-46.0
	(b) Compressed air systems for compression chambers	> 200	Dew Point (^oC)	-49.0
2	Compressed air systems for cylinder filling.	200 and 300	Dew Point (^oC)	-52.0
3	Ships HP Air production systems with purification.	-	Dew Point (^oC)	-55.0
4	Air supplied in cylinders for aircraft	-	Dew Point (^oC)	-61.0

A solution has been developed to overcome the potential issues discussed above which pertain to the BA testing regime. This solution uses a portable on-line continuous multi gas analyser designed to detect multiple gas contaminants of compressed BA and meet the requirements of most International BA Standards, Table III.

Table III: International Breathing Air Standards Limits

	International Breathing Air Standards/Recommendations					
	GERMANY DIN 3188 (1984)	*UK BS 4275 (1997)*	*HOLLAND ADMP-1 NL*	*USA FED SPEC BB-A-1034B*	*AUSTRALIA AS2299-1979*	*NEW ZEALAND DZ5813/1*
Oxygen	20-21%	20-23%	21%	20-22%	20-22%	20-22%
Carbon Dioxide	800 ppm	500 ppm	500 ppm	500 ppm	480 ppm	480 ppm
Carbon Monoxide	30 ppm	5 ppm	10 ppm	10 ppm	10 ppm	10 ppm
Oil Vapour	-	0.5 mg/m^3	0.3 mg/m^3	0.005 mg/m^3	1 mg/m^3	1 mg/m^3

The unit provides continuous real time measurement of Carbon Dioxide (CO_2), Oxygen (O_2), Carbon Monoxide (CO) and Hydrocarbons (HC), with each parameter shown on an individual display. The current trial unit does not include a dew point sensor as this is already proven technology and will be incorporated into the final production unit.
Oxygen and Carbon Monoxide are detected using electrochemical cells, Carbon dioxide and Hydrocarbons are detected using Infra Red (IR) sensors. Air is delivered to the unit via 6mm OD Push fit connector. The pressure at the inlet must not exceed 10 bar. The sample pressure is then internally reduced and carried to the sensors via internal flow adaptors and tubing.

The unit can be installed as a permanent monitor for continuous on-line analysis or alternatively it can be operated from internal rechargeable batteries making ideal for remote locations.

Audible and visual alarms are triggered when any of the gases exceed their alarm thresholds, enabling the filling process to be shut down and the source of contamination to be investigated. Following contamination the analyser will return to normal levels when subjected to clean air. Alarms will also activate when the airflow or battery life is insufficient for the unit to operate adequately. If required the gas alarm set point can be adjusted between the sensor ranges shown, in Table IV, to fine-tune to the particular system that it is installed. The monitor also has a built in data logging capability, which can be configured for either survey or analysis. The data logger can be configured to measure any combination of gases with sampling intervals between 10 seconds and 30 minutes.

Table IV: Sensor ranges

Oxygen	Oxygen sensor with 2-3 years life in air at normal atmospheric pressure	
	Range	0 – 100% O_2
	Resolution	0.1%
	Accuracy	± 1% of reading, ± 0.2% O_2
Carbon Monoxide	CO Sensor	
	Range	0 – 50 ppm
	Resolution	1 ppm
	Accuracy	± 3% of range
Carbon Dioxide	Low power, long life infra red sensor with microprocessor applied temperature compensation and linearisation	
	Range	0 – 2500 ppm
	Resolution	1 ppm
Hydrocarbon	Heated infra red hydrocarbon sensor with microprocessor applied temperature compensation and linearization	
	Range	0 – 100 ppm (N-Heptane)
	Resolution	1 ppm

FEEDBACK FROM MINOR TRIALS UNITS

Documented feedback from HMS Excellent (fire fighting training establishment) for the automated cylinder charging system has shown that:

All users have found the system easy to use and verify it is a vast improvement over current manual fill charging panel. The system has been used both by fire school staff and selected RN advanced courses (ISSC onwards). It is proving to be robust and safe in a high use environment.

As the unit does not need to be monitored, it frees up manpower to perform other tasks during fire school exercises.

Feedback from the minor trials unit fitted onboard HMS Ocean mirror that of the performance received from the fire training school.

A fully shock and EMC tested unit has been developed and will be incorporated into the cylinder charging system for the new T45 destroyer.

CONCLUSIONS

The investigation into the procedures and operation of the manual-charging panel identified a number of potential shortfalls. The developed solution has addressed these shortfalls by:

i. Automating the charging cycle, which has reduced the level of human interface and hence risk.
ii. Utilizing a slow exponential fill profile to the cycle, which maximizes the mass of breathing air charged.
iii. Introducing a method of control to the fill profile, which maintains flow rate within operational capabilities of the point of service filtration.
iv. Introducing on-line air quality monitoring, which can be used to assess the quality of air during charge or for trend analysis purposes as an input to an overhaul /repair on condition policy.

REFERENCES

1. Ministry of Defence, Defence Standard 68-284, “Compressed Breathing Gases for Aircraft, Diving and Marine Life-Support Applications” Issue 2, 8 November 2002

Author’s Biography

After joining British Petroleum (BP) as an officer cadet, Mr Jim Bentley served 10 years before the mast as a marine engineering officer. On leaving BP he was recruited by the Ministry of Defence serving roles in technical documentation/logistics and submarine hydraulic systems before forming the research and development cell of the Marine Auxiliary Systems Integrated Project Team. In this role he has developed solutions to in-service problems by the application of new or emergent technologies. As the competent authority for naval pressure vessels he is a member of many industry sector working groups and committees (i.e. BSI, HSE etc). Mr Bentley joined Imes Ltd in March 2005 on a three-year secondment. His current role as Chief Engineer Pressure Systems and NDE applies many of the techniques developed during his time with MoD to the asset management and residual life prediction of pressure systems and structure.

Mr Terry Manders graduated from Loughborough University with an Honours degree in Mechanical engineering in 2001. Since then he has been working for Hale Hamilton developing and integrating control systems with new automated cylinder filling technology to produce customised solutions for industrial gas companies and the Royal Navy.

Mr Steve Burchill joined the Ministry of Defence as a school leaver in September 1986 and subsequently completed the 4 year Technician Apprenticeship Scheme. Enjoyed various posts within Defence Procurement and Logistics Organisations over the last fifteen years with the last six years being spent as a Subject Matter Expert within Compressed Air and Systems Engineering.