Development and Certification of a Skid Mounted AMB Controller for Hazardous Area Installation

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***Abstract*—Active magnetic bearing (AMB) controllers for hydrocarbon and other hazardous area applications are normally installed within a control room inside a safe (unclassified) area. This article describes the design and certification of an AMB controller for skid mounting within the hazardous area, drawing on recent development of a first of class system.**

The design challenges raised by the environmental requirements for outdoor installation are discussed together with the challenges resulting from the hazardous area certification requirements.

The routes to hazardous area certification considered during the early phases of the development project are presented together with a description of the route finally chosen.

I. INTRODUCTION

A. *Why a Skid Mounted Controller*

Active magnetic bearing (AMB) control systems used in hydrocarbon service are typically installed within a control room in an unclassified area. Installing the AMB controller on the equipment skid within the hazardous area can reduce the equipment footprint and eliminate costly cabling. Despite the limitations this creates for physical access to the controller, the secure remote connectivity provided by advanced digital AMB controllers allows monitoring, tuning and diagnostics to be performed.

In a typical AMB installation the plant control room where the AMB control panel is installed may be several hundred meters from the machinery skid. A schematic of such a system is shown in Fig. 1, and an example is given in [1]. Running the cables between the control room and the machine skid requires costly expenditures during multiple phases of the project, including the design engineering, procurement, installation and commissioning phases. The following paragraphs describe the relevant activities on a typical new design hydrocarbon turbo-expander project. Rough order of magnitude (ROM) estimates of the cost and schedule impact to the engineering, procurement and construction company (EPC) during each phase are given in Tables I and II.

The design engineering phase of such a project will include selection of suitable cable, including consideration of cable losses; design and sizing of the control room; design of cable routing systems and building cooling systems; and possibly electrical junction boxes.

The design and sizing of the control room will need to consider the placement of the AMB control panel together with consideration of cable entry to the building. The connections to associated control systems located within the same building would also need to be designed. This will typically involve co-ordination between the AMB vendor, the original equipment manufacturer (OEM), the EPC and possibly the end user. It is inevitably a time-consuming process that will typically be incurred on each new installation design.

Design of cable routing systems, including cable trays and/or conduits to run between the control building and the equipment skid, must include consideration for maintenance of minimum separation distances between power and signal cable runs – not only between AMB power and signal, but also with third-party equipment such as motor drive cables. This activity may again require co-ordination between AMB vendor, OEM and EPC. Design of the building cooling systems will need to accommodate the additional heat load from the AMB control panel, and additional electrical junction boxes may be needed on the machine to terminate the field cables for the AMB, requiring additional design.

During the procurement phase, procurement costs associated with the additional elements previously identified will be incurred:

- AMB field cables
- Larger control building
- Cable trays/conduits and associated fixtures
- Larger cooling system for control building
- AMB junction boxes
- Signal Filters/Amplifiers

The installation phase will include the following activities:

- Installation of AMB control panel in the control building
- Installation of cable trays/ conduits
- Installation of skid-mounted junction boxes
- Installation of cables and connection to the AMB control panel and junction boxes
- Loop and insulation testing of the AMB field cables

Additional commissioning activities related to the AMB controller installation in a plant control room are primarily associated with connecting the AMB controller to the job cables and the plant DCS and re-testing the system. In many instances the testing at the OEM factory will have been conducted with a shorter set of test cables. Consequently, following the installation on-site, the system must be verified for:

- Correct connectivity
- Correct cable routing (impacting AMB system noise levels)
- Correct tuning of AMB system dynamics

TABLE I. COSTS ASSOCIATED WITH AMB CABLES AND CONTROL ROOM INSTALLATION

Project Phase	ROM cost to EPC ($K USD)
Design	20
Procurement	50
Installation	20
Commissioning	15

In contrast, a system that uses a skid mounted hazardous area controller eliminates these costs, particularly where the controller remains installed on the skid for transportation from the OEM to the end-user site. There are, however, additional costs associated with control cabinet environmental protection (temperature, shock and vibration) and hazardous area certification, which will be discussed in the subsequent sections.

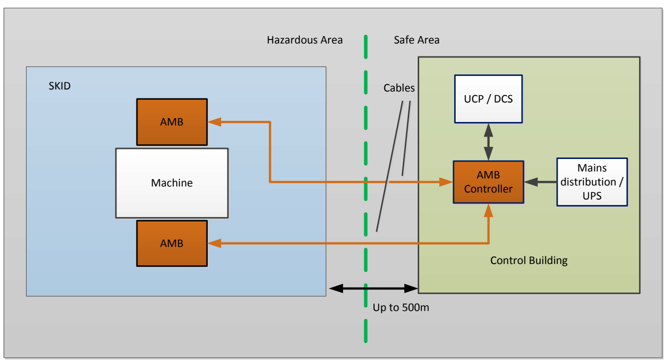

Figure 1. Schematic of typical AMB installation with the AMB controller in a safe area.

B. *First of Class System*

A skid mounted AMB controller has been developed for turbo-expanders operating in gas processing plants.

Perhaps more significant than direct costs associated with AMB cable and control room installation is the schedule impact due to AMB controller installation at site. The NGL market in particular has placed a premium on overall installation/commissioning time. Modern schedule constraints effectively rule out the supply of equipment requiring additional site installation or modification. It is highly desirable for OEM equipment to arrive "ready for use".

During the OEM design and engineering phase, significant time savings are realized with a skid mounted AMB controller. The primary reason is a reduction in the drawing review and approval process. A control room installed AMB controller requires a detailed review and potential modification of the AMB control cabinet for integration into the EPC/End User's design. This review and approval process can take weeks, especially if drawings are passed and checked between multiple parties. A skid mounted AMB controller is completely independent of an EPC/End User control room design. As such, the OEM can move much quicker through the overall design, engineering and fabrication process. Only a cursory review of interface drawings remains for the EPC to gain an understanding of necessary power connections.

TABLE II. SCHEDULE IMPROVEMENTS ASSOCIATED WITH SKID MOUNTED AMB CONTROLLERS

Project Phase	Schedule Improvement (weeks)
Design & Engineering	4-6
Installation	2-4
Commissioning	1-2

The schematic of the installation of the skid mounted AMB controller is shown in Fig. 2. The uninterruptible power supply (UPS) system is located within the safe area in order to eliminate the risks and challenges of providing a hazardous area certified battery system.

In reviewing the literature, the authors were unable to identify any applications where a hazardous area AMB controller was explicitly described. There are, however, numerous applications of controllers requiring an unclassified area, that are installed on skids in classified areas with suitable purge / pressurized enclosures, such as those commonly used for seal gas heaters.

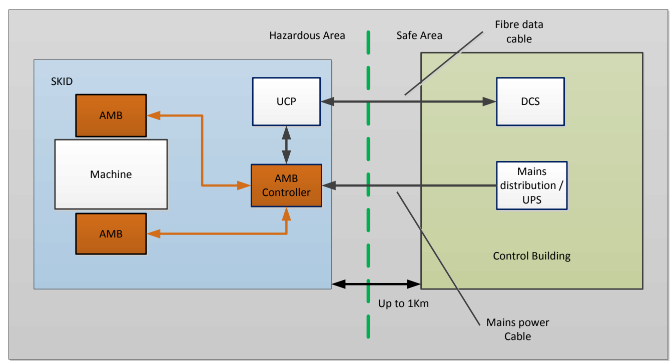

Figure 2. Schematic of proposed hazardous area AMB controller installation.

II. HAZARDOUS AREA CERTIFICATION

A. *Certification and Environmental Targets*

Hazardous area certification is intended to protect against the risk of electrical equipment being (or becoming) an ignition source within a potentially explosive atmosphere. A range of design methodologies are available to provide what is known as a Hazardous Area (or HazLoc) design (North America) or ATEX (ATmosphere EXplosive) design (Europe).

Hazardous area certification splits into two main categories:

- The Class/Div system used within North America and those jurisdictions following North American standards
- The Zone classification system based on the IEC 60079 series of standards [2]

As shown in Fig. 3, the North American system is based on the National Electric Code (NEC) standard NFPA 70 [3]. Class categories are allocated to gas and dust hazards, with Class 1 being applicable to explosive gas hazards. NEC also allows for a Zone classification system which is harmonized with the ISO standards.

Within the Zone classification system, zones are allocated to gas and dust hazards, with Zone 0, Zone 1 and Zone 2 being applicable to explosive gas hazards.

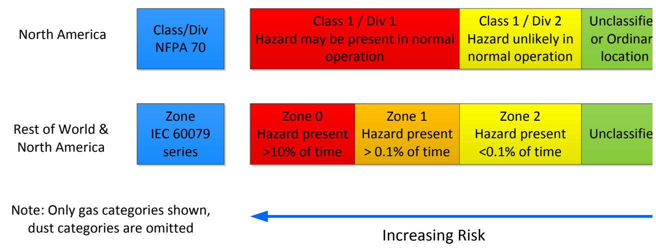

Figure 3. Overview of hazardous area classifications for explosive gas hazards.

Within each system, risks are graded by the different zones or divisions. As can be seen in Fig. 3, there is not a one–to-one alignment between the Class/Div system and the Zone system. Depending on the risk level (zone or division), different hazardous area protection methodologies can be deployed. Again there is not direct overlap between the North American and ISO systems, with some methodologies only being permitted within one of the systems. A good overview of the methodologies that can be deployed within each division or zone can be found in [4].

The classification systems also include categorization of the gas types and the allowable maximum temperatures. The target application for the first installation of the first in class system is defined as Class 1/Div 2, Groups C&D T3, where T3 defines a maximum surface temperature of 200ºC (392ºF).

For widest commercial applicability it is desirable for any equipment that is designed to also be applicable to Class 1/Div 1 and Zone 1 and Zone 2. For the first installation, however, whilst the other target application spaces were considered, the focus was primarily on achieving Class 1/Div 2 certification within the required timeline, and so some design and certification decisions have been made which may need modification for the other target markets.

The thermal specification of the first target application is outdoors mounted in direct sunlight with an ambient thermal environment of -29ºC to +43.3ºC (-20ºF to 110ºF). Other applications are under consideration with a low temperature of -40ºC (-40ºF).

Because the AMB controller will be skid mounted during the transport from the OEM to the end-user site, the system design must allow for the shock and vibration likely to be seen during transport of a large machinery skid. In operation the shock and vibration seen by the AMB controller will be low, due to the use of AMBs within the machinery, although during aerodynamic upset conditions vibrations due to pressure pulses within the gas stream may occur.

B. Routes to Certification

For a Class 1/Div 2 application the equipment must be accepted by the Authority Having Jurisdiction (AHJ). The route to acceptance will depend on the AHJ, but the surest way to ensure acceptance is to have the product certified (or listed) by a Nationally Recognized Testing Lab (NRTL). The turbo-expander OEM for the first of class system has specified a UL/FM certified panel to satisfy the demands of various end users surveyed. Consequently the manufacturer's declaration of conformity (MDOC) route shown in Fig. 4 has been rejected.

As shown in Fig. 4, there are two possible routes to obtaining a UL listed panel. The first is a conventional certification where a fixed product design is submitted to the NRTL, which conducts a type test on the product prior to issuing a certificate which will cover all identical units manufactured at the same location under the same controls. The second is the UL panel builder route. In this system, the certification is not so much of the product as the manufacturer. This has the advantage that changes to the design can be made without having to recertify the product. For the panel builder program for unclassified locations it is acceptable to use CSA listed components within the panel, under a memorandum of understanding between UL and CSA. However, for the hazardous area panel builder program, the Memorandum of Understanding does not apply and only UL listed parts may be used within the controller. This is a significant limitation, but despite it, the panel builder route to certification was chosen. The impact of this limitation will be discussed in the section on system design.

The standards with which the AMB vendor needed to comply for the hazardous area panel builder program were:

- UL 508A [5] – for ordinary locations
- NFPA496 [6] – purged pressurized enclosures
- UL1203 [7] – for explosion proof construction
- UL698A [8] – Control panels for hazardous locations

UL 508A in turn calls up many component standards, and only components listed under those standards may be used within the panel.

The Zephyr controller manufactured by AMB vendor Waukesha Magnetic Bearings has historically been certified under the International Electrotechnical Commission (IEC) CB scheme according to IEC 61010-1 [9] by TUV.

To use this controller within a certified control panel it was necessary to first refresh the CB certification, to allow for some recent design modifications and cover the national differences in the US version of standard UL 61010-1 [10]. The TUV CB file was then passed to UL to allow them to cross-list the Zephyr controller. The cross-listing process is shown schematically in Fig. 5.

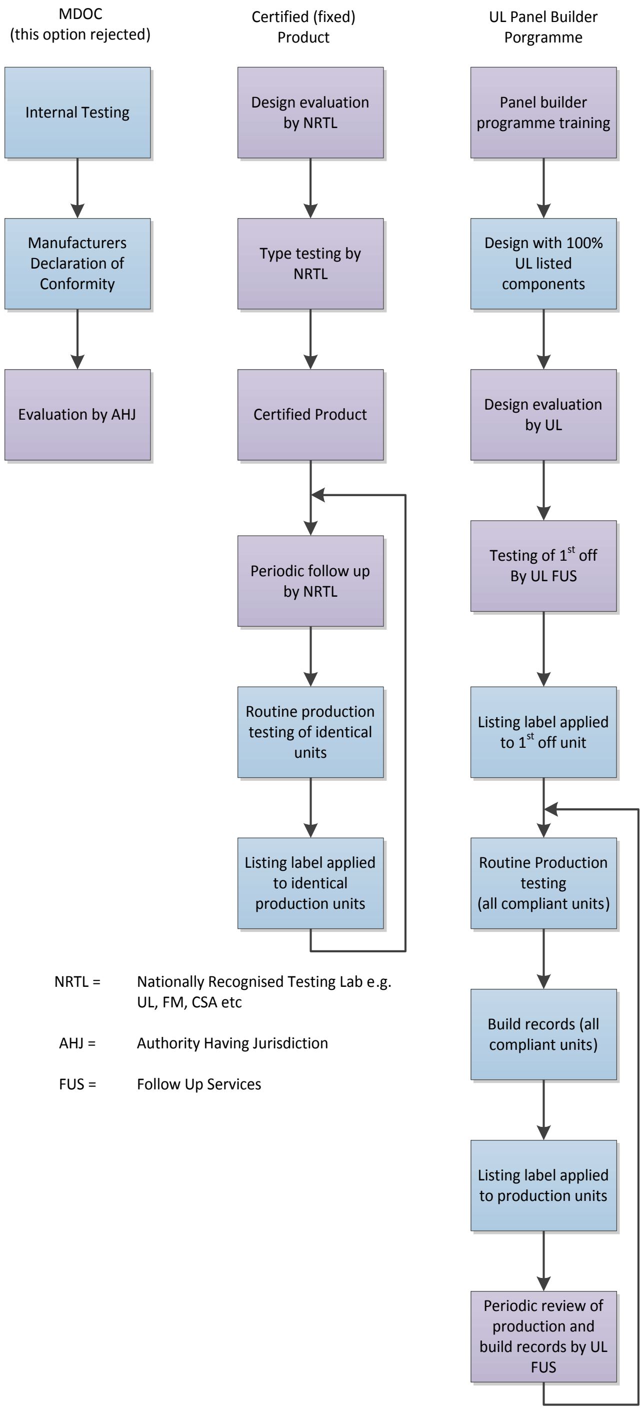

Figure 4. Schematic of possible routes to acceptance by AHJ.

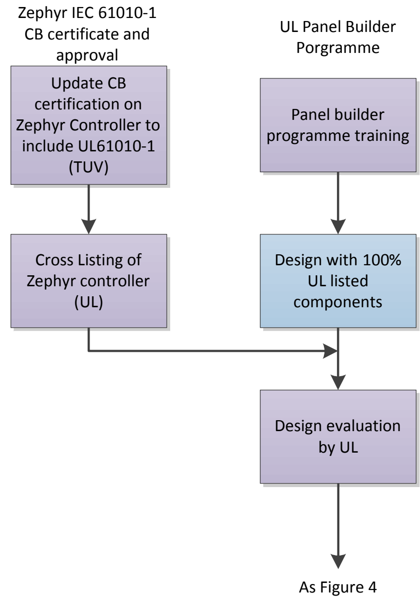

Figure 5. Schematic of cross-listing process.

III. SYSTEM DESIGN

A. Design Concept and Challenges

It was clear from the outset that the Zephyr controller on its own would not be suitable for a Class 1/Div 2 environment, due to the large rating of the amplifiers driving current in the AMB windings. There were two possible solutions acceptable in a Class 1/Div 2 application: a purged and pressurized enclosure; or a flameproof enclosure. The second option was rejected due to the very large size of the required enclosure and the anticipated problems in cooling the controller within such an enclosure.

In the purged and pressurized enclosure route that was selected, the equipment to be protected is mounted within an enclosure which in normal operation is filled with non-explosive gas at a slight over-pressure to the ambient pressure. The gas in the enclosure is managed by a purge controller, whose function is to first purge the enclosure, by passing a known volume of non-explosive gas through the enclosure during what is known as the purging cycle, and then once purging is completed maintaining the over-pressure with a controlled leakage to the outside.

Because the enclosure must maintain an overpressure, the cabinet cooling systems must be essentially closed loop (i.e., with minimal exchange of air between the inside and outside of the cabinet). Three cooling solutions were considered:

- Air/water exchanger
- Air conditioner
- Vortex cooler

The ambient temperature range, external to the cabinet, is -29ºC to +43.3ºC (-20ºF to 110ºF), but the operational temperature range of the Zephyr controller and other electronics within the cabinet is 0ºC to +40ºC (32ºF to 104ºF). This raised the first major design challenge.

Total heat dissipation within the cabinet when operating at maximum load was estimated at 1200W. A vortex cooler to handle this heat load would require 4000Nl/min, which was considered an unacceptably high volume in addition to presenting problems with the management of the overpressure within the cabinet.

The air/water exchanger solution was discounted due to the very low ambient temperatures that the system is likely to see. This left the air conditioner solution as the only viable option to handle the high end temperature.

A packaged solution comprising a UL listed NEMA 4X enclosure with a UL listed MiniPurge controller from Expo Technologies was selected. This purge controller is only rated for operation above -20ºC (-4ºF) and so the next design challenge was how to handle startup in low temperature conditions. Any heaters necessary to raise the temperature to the point at which the purge controller can be started must be protected by some other hazardous area protection method. The method selected was flame proof (also known as explosion proof) construction for the heater circuits.

To minimize heat loss from the enclosure during the low temperature start up condition, the enclosure walls, roof and door were insulated (allowing for reduced heater power requirements). This also helped minimize the heat flux into the cabinet during operation at high ambient temperature, resulting in a smaller air-conditioner. Heat flux into the cabinet due to solar radiation is further reduced by fitting of a sun canopy.

A schematic of the selected thermal management solution is shown in Fig. 6.

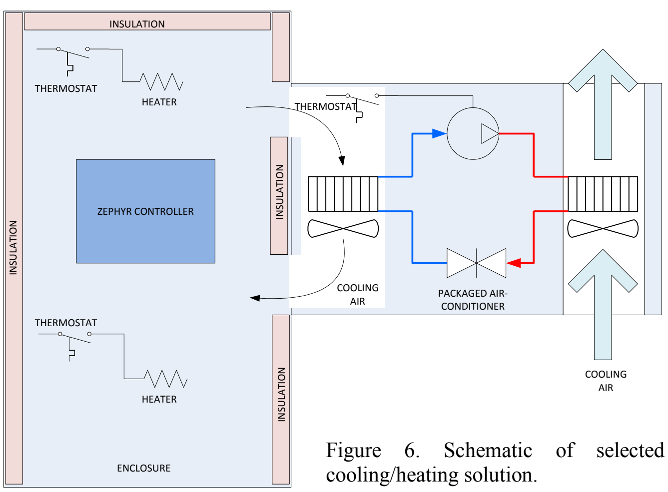

Figure 6. Schematic of selected cooling/heating solution.

In order to facilitate startup during low temperature conditions, a mechanical dial thermometer was included in the enclosure and a NEMA 4X viewing window was added to the enclosure to allow the thermometer to be viewed. Fitted inside the pressurized enclosure is a UL listed MiniPurge type X controller. It is fitted inside because the ambient temperature range at the final installation site is below the minimum operating temperature of the purge controller. The type X indicates an automatic purge controller. An automatic purge controller is not required for Class 1/Div 2 gas groups C&D, but is being used because the manual MiniPurge type Z controller has an operator handle which would have to pass through the enclosure wall, and this would not meet NEMA 4X requirements. Also, the temperature gradient along the handle into the purge controller may have been below the minimum operating temperature of the purge controller. If a purge system failure occurs, a signal is transmitted to the Unit Control Panel (UCP) via an Intrinsically Safe (IS) changeover contact. Such a failure will result in the removal of main power from the AMB panel, but for Class 1/Div 2 this does not need to be fully automatic.

The construction of the flame-proof heater circuit comprises a UL listed flame proof junction box mounted on the outside of the main enclosure. The box has incoming conduit for the 120V AC heater supply and outgoing explosion proof cable glands which allow entry of the heater cables into the main enclosure. In line with the heaters are flame proof thermostats. The selection of the heaters was challenging due to limited availability of UL listed heaters which were acceptable according to UL standards.

The heaters are set to switch off once the temperature inside the enclosure is above 10ºC (50ºF).

A schematic of the hazardous area protection scheme is shown in Fig. 7. Fig. 8 shows the purge controller (including status indicator) and thermometer.

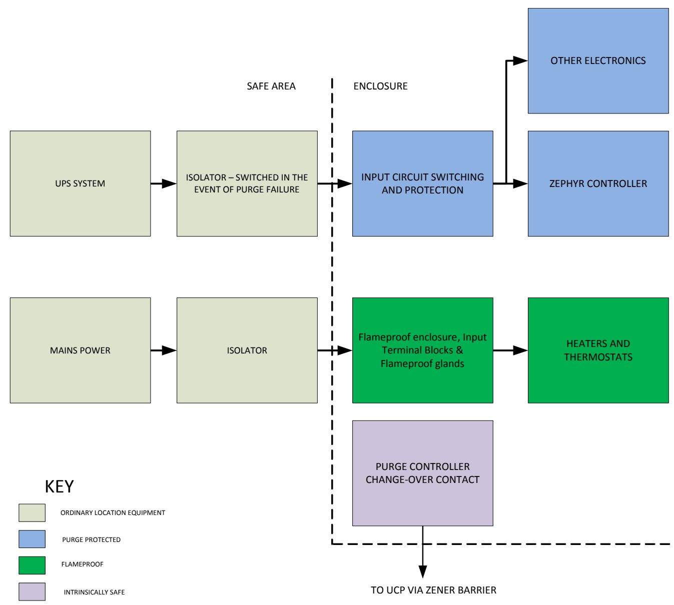

Figure 7. Schematic of hazardous area protection.

When putting the system into operation, the first element activated is the heaters. The user waits until the ambient temperature is above -20ºC (-4ºF) according to the dial thermometer, at which point the purge air supply is activated. Once the temperature has reached 0ºC (32ºF) and the purge controller indicates OK (i.e., the purge cycle completed successfully), the main power isolator on the output of the UPS system would be activated by the user, applying power to the cabinet.

During operation, if the temperature inside the cabinet drops below 0ºC (32ºF), an additional thermostat will trigger a trip of the AMB system to ensure that components are not operated outside of their rated temperature ranges.

Figure 8. Purge controller and thermometer.

Locating the UPS and its associated isolator in the safe area away from the AMB controller increases the risk of mis-operation through operator error. The alternative of locating the UPS and its batteries inside the AMB panel, however, was considered too severe a challenge, both in finding a robust technical solution, but also remaining within the target budget.

Because the AMB panel is installed in the hazardous area, the door on the panel cannot be opened in normal operation (when the system is energized). This results in strong requirements for the data communication capabilities with the AMB servo controller and the PLC monitoring the bearing temperatures.

As with all elements of the cabinet, the data communications architecture, shown in Fig. 9, needs to be suitable for Class 1/Div 2 application. The use of a multi-mode fiber optic data link to the control building allows for extended distances, but also eliminates any possible source of ignition from the control building. Within the skid the UCP and AMB control cabinet communicate using standard Cat 6 cables. The network switch within the UCP is a non-sparking unit suitable for Class 1/Div 2. The media converter within the AMB cabinet also acts as a switch and is purge protected (i.e., when power is removed from the AMB cabinet, the media converter is de-powered).

Both the resistance temperature detector (RTD) monitor and the AMB servo controller have two separate Ethernet interfaces, each with Modbus server connections sent to the UCP and Webserver connections sent to the control room via the fiber optic link.

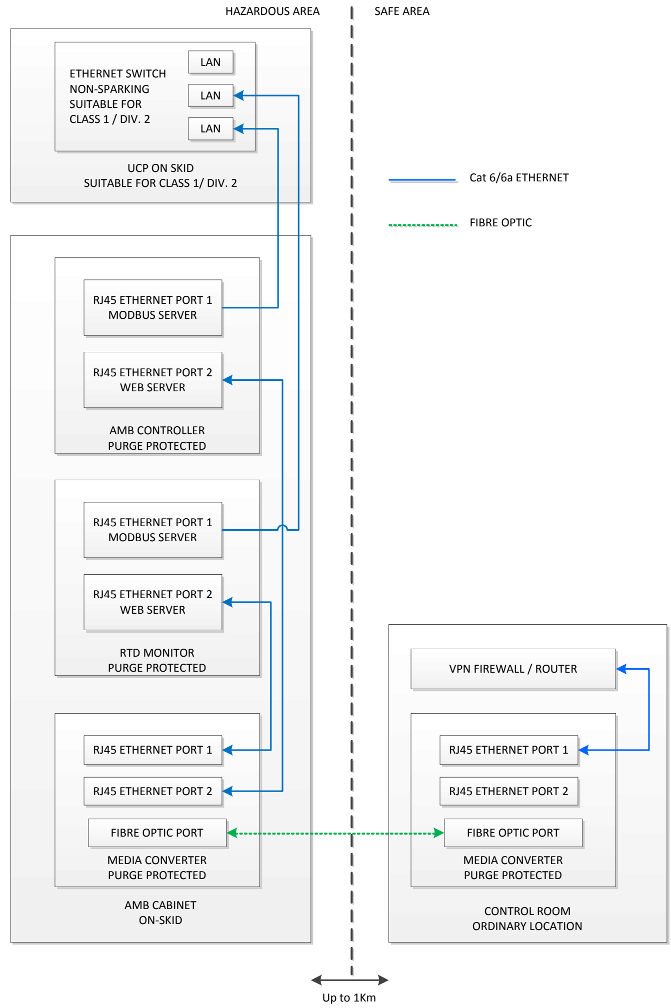

Figure 9. Data communications schematic.

Within the control room there is facility for either a local connection using a laptop to allow an on-site engineer to commission the system, or a (optional) connection to a VPN/firewall router to allow remote commissioning and support. Because access to the cabinet is limited when operating in the hazardous area, the built in measurement capabilities of the Zephyr controller (including built in transfer function measurement, Fourier analysis and order tracking) are critical to successful commissioning of the equipment.

The final design consideration was the transportation of the AMB control cabinet from the OEM factory to the end-user site. Because the control cabinet will be shipped fitted to the equipment skid, it will see high shock and vibration during transportation. The options considered to handle these were:

- Removal of critical components for transportation
- Mounting the AMB cabinet on AV mounts

The first option was discounted because it conflicts with the aim of keeping commissioning at the end-user site to an absolute minimum. Consequently the second option was selected, but was modified so that following installation the AV mounts are bridged by rigid elements so that cabinet is rigidly mounted to the skid. As discussed in section II, skid vibration levels are expected to be low during operation.

The completed panel, with the front door open, is shown in Fig. 10 and the panel fitted to the skid (with the AV mounts) is shown in Fig. 11.

Figure 10. AMB controller enclosure with front door open.

Figure 11. AMB controller enclosure mounted to the skid.

IV. TESTING

A. Testing of the Purge and Environmental Systems

Testing of the purge system comprises a leakage test and an overpressure test (in addition to the routine manufacturing tests on the purge controller). The leak test showed an acceptable leak rate in normal operation (Fig. 12). The majority of the leakage was through the drain of the air conditioning unit.

The system is fitted with a pressure relief valve which includes a flame arrestor. The overpressure test is to verify that the enclosure does not deform when subjected to a pressure greater than the nominal lifting pressure of the relief valve. This should not occur in practice and can only occur if the pressure regulation in the purge controller has failed. The relief valve nominal pressure is 10mbar and the enclosure was tested at 18mbar overpressure for two minutes without any deformation of the enclosure.

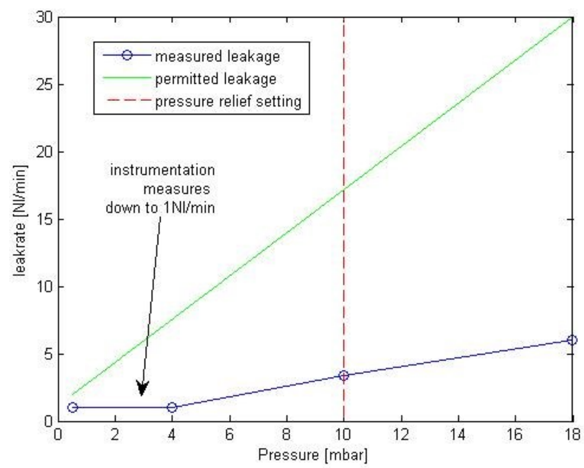

Figure 12. Leak test results.

Thermal tests were also performed on the first of class unit, including:

- Heat run tests
- Heater tests

Because the heater thermostats were set at 10ºC (50ºF) and during the testing the external ambient was above 10ºC (50ºF), heaters of equivalent power were used for this test (mounted in the cabinet adjacent to the real heaters), with a separate thermostat set for 40ºC (104ºF), the maximum set-point. This allowed the required heating capacity to be confirmed by a simple temperature rise test without the need to chill the ambient temperature to -29ºC (-20ºF). The results of this heater test are shown in Fig. 13. The rise above ambient reaches 23ºC (73ºF) before the thermostat switches, with the thermostat hysteresis giving rise to the saw tooth type curve. Extrapolating the curves beyond this switching point gives the required 29ºC (52ºF) temperature rise.

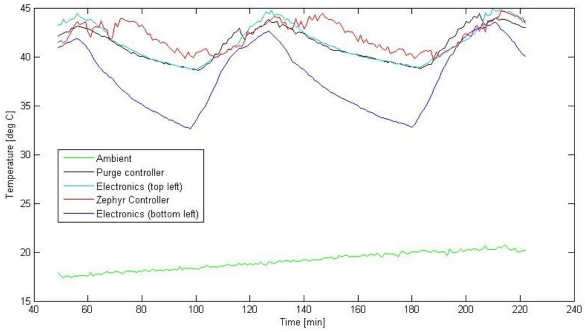

Figure 13. Heater test.

Heat run testing was conducted with the Zephyr controller fully loaded (15A in all 10 amplifiers) and the ambient surrounding the cabinet raised to 45ºC (113ºF). The results of the heat run testing, shown in Fig. 14, confirm the acceptability of the surface temperature of the enclosure for the T3 rated gas group.

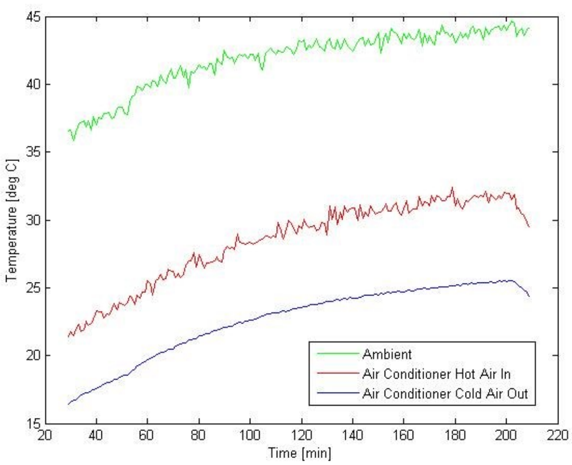

Figure 14. Heat run test results with controller at rated load.

B. *Preliminary Factory Test Results*

At the time of writing, the rotational testing of the first turbo-expander coupled to this hazardous area AMB controller has started, with runs on open loop air to the maximum speed of 30,000rpm completed. No issues with the AMB controller have been identified during these runs.

Fig. 15 and 16 show the bode plots of the first order vibration and current captured during the run up using the internal instrumentation capabilities of the AMB controller. At just over 10,000rpm the effect of the tracking notch filters is seen, with a reduction in the vibration levels.

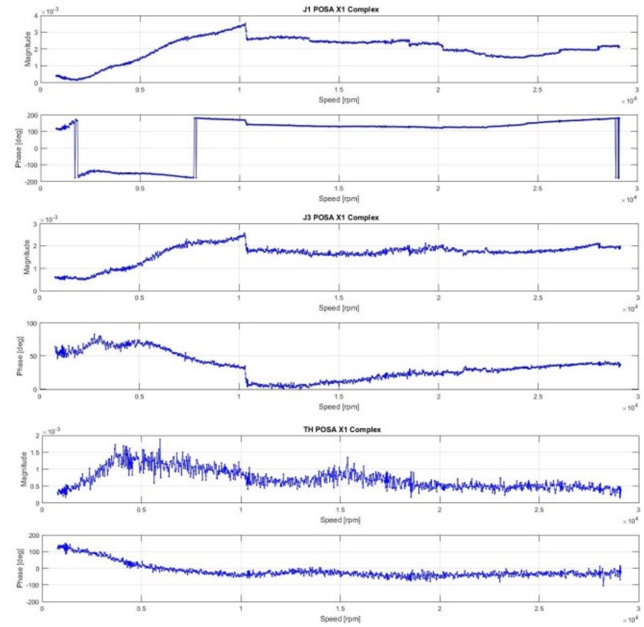

Figure 15. Position 1x Bode plots during run up to 30,000rpm. Magnitude in mm.

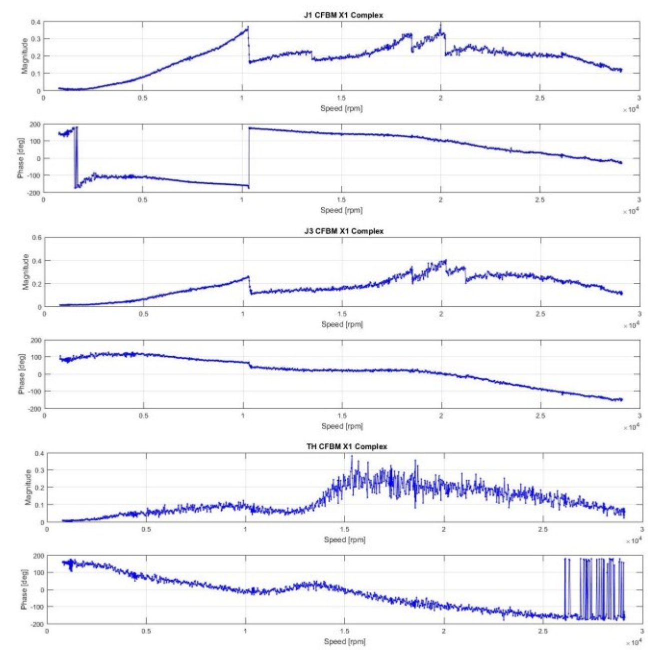

Figure 16. Current 1x Bode plots during run up to 30,000rpm. Magnitude in Amperes.

V. CONCLUSIONS AND FUTURE WORK

A unique first of class skid mounted hazardous area AMB controller designed for a wide range of environmental conditions has been successfully demonstrated, including heat run testing and rotational testing.

This new design of controller shows significant cost benefit compared to conventional control room mounted controllers due to the elimination of many design, installation, and commissioning tasks which would normally be associated with the end-user site.

Further work on the heaters necessary for low ambient temperatures will continue in order to complete the final stages of certification and to investigate solutions for extended environmental conditions including startup at -40ºC (-40ºF).

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