DNV·GL

ROOT CAUSE FAILURE ANALYSIS INVESTIGATION REPORT

Weymouth Compressor Station September 30, 2020 Blowdown Event

Algonquin Gas Transmission, LLC
Subsidiary of Enbridge Inc.

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Objective:

Pursuant to PHMSA ACAO dated October 30, 2020 (1-2020-014), complete a root cause failure analysis facilitated by an independent third party that documents the decision-making process and factors contributing to the September 30, 2020 blowdown event at the Weymouth Compressor Station, including findings and lessons learned.

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Incident investigation, BowTie, BSCAT, Compressor Station, blowdown, emergency shutdown, ESD

EXECUTIVE SUMMARY

DNV GL USA, Inc. (DNV GL) performed a root cause failure analysis (RCFA) of an unplanned event that triggered the emergency shutdown (ESD) system and subsequent blowdown at the Algonquin Gas Transmission, LLC (AGT)[1] Weymouth Compressor Station in Weymouth, Massachusetts, on September 30, 2020. The ESD system is designed to monitor various safety and operating parameters, isolate and depressurize the system, placing the station into a safe state. In this instance, depressurization resulted in a release of approximately 195,000 cubic feet (195 mscf) of natural gas. The Amended Corrective Action Order (ACAO) issued to AGT by the Pipeline and Hazardous Materials Safety Administration (PHMSA) requested that an independent, third party conduct the RCFA, for which DNV GL was subsequently approved by PHMSA.

DNV GL provides independent investigations using specialists trained in investigation techniques, complex technologies, and difficult or challenging environments. The Barrier-based Systematic Cause Analysis Technique (BSCAT™), used to evaluate events, combines traditional technical and management system root cause analysis with modern barrier-based risk assessment.

On October 12, 2020 personnel from DNV GL mobilized an investigation team to determine the initiating event (immediate cause) that triggered the ESD event and begin collecting evidence (documentation, interviews, etc.) for the RCFA. Two members of DNV GL's team travelled to Waltham, Massachusetts, and spent the week of October 12, 2020 at an AGT office in Waltham, including two days at the Weymouth Compressor Station site.

The objectives of the RCFA were to identify the most probable direct (immediate) cause and root cause(s) of the ESD that resulted in the blowdown event at the Weymouth Compressor Station, and document the decision-making process and the factors contributing to the event, including findings and lessons learned. DNV GL's work involved reviewing documentation and conducting interviews associated with the design, installation, service, and operational history of the station, including associated procedures and practices. These activities were the main inputs to four (4) causal analysis workshops, facilitated by DNV GL, that utilized the BSCAT™ to document and evaluate the effectiveness of barriers in place to prevent the immediate cause that led to the ESD event. The team discussed recommended improvements to lower the likelihood of a similar event from occurring in the future.

The conclusions of this RCFA are based on findings from the document review, site visit to the Weymouth Compressor Station, interviews, and BSCAT™ workshops facilitated by DNV GL. DNV GL reserves the right to modify or supplement the conclusions represented herein should new information become available.

The result of the investigation identified that loss of power on a 129 V_{DC} circuit triggered the ESD event. Two immediate cause scenarios that may have led to an open circuit condition on the 129 V_{DC} circuit were evaluated:

Scenario 1 - <u>*Open circuit caused by faulty equipment, loose connection, or damage during shipping*</u>.

Scenario 2 - <u>*Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction*</u>. Scheduled ground compaction activities were occurring at the compressor station at the time of the event. During interviews and while DNV GL was on site, the vibrations caused by this activity were described as unusually strong.

[1] Algonquin Gas Transmission, LLC is a subsidiary of Enbridge Inc.

The results of the RCFA identified three (3) primary barriers that could be implemented and/or improved to reduce the likelihood of a similar event from occurring in the future:

- Requirements and conditions for storage of electrical equipment and components.
- The commissioning plan and procedures (including onsite wiring assembly).
- The risk assessment for non-routine activities, such as the large-scale ground compaction that was performed during commissioning at the Weymouth Compressor Station.

The lessons learned and corresponding recommendations for improvement pertaining to these three barriers are discussed below.

1. **Clear Specifications and Communication with Vendors**

Currently, the specifications given by AGT to their vendors are focused on the requirements for assembly and testing of components, including requirements for how the components are marked, packaged, stored, and transported. These requirements provide assurance that the necessary actions to be taken prior to and during installation are understood. By communicating any additional requirements for special circumstances, such as unanticipated extended schedules and extended storage, AGT can have further assurance that risks associated with storage during future delays are appropriately managed.

2. **Consideration of Risks associated with Unanticipated Extended Schedules**

Implementation of a working document or internal standard that addresses considerations to be made when projects are delayed or put on hold for long periods of time will help ensure items, such as hazard identification, long-term storage of components, and communication of special circumstances to vendors will be addressed.

3. **Improvements to Wiring Standards**

The existing wiring standards and requirements do require ferrules on terminal blocks; however, installation requirements (i.e. size and manufacturer) of the ferrules are not included within the standard. Revising the standards regarding installation of ferrules and terminal blocks will help ensure proper application of ferrules in the future.

The current practice is for a tug test to be performed by the Electrician when wiring is initially installed; however, only a visual inspection is required as part of pre-startup checks. Revise the electrical standards and/or procedures to require integrity testing of electrical connections (e.g., tug test) after installation and during commissioning to provide assurance that the connections are sound in future projects and applications.

4. **Increased Awareness of non-routine Activities and Require Risk Assessment**

The large-scale ground compaction activity that was being performed as part of construction was not identified as a non-routine activity, because compaction is commonly done; however, in this case, the magnitude and timing of the activity (in terms of vibration) was beyond what is typical. Increasing awareness among staff and requiring risk assessment for non-routine, rarely-conducted activities or those that differ from the norm will help ensure the impacts on facility components and equipment, as well as safety, are understood and managed appropriately.

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Definitions and List of Acronyms

Definitions of the terms and acronyms used with the BSCAT™ methodology are provided in the following table.

Term	Definition
Barrier	Design features, engineered systems, or administrative controls that prevent the causes or mitigate the consequences of a deviation from normal operation/intent.
Basic Cause (BC)	A fundamental, underlying, system-related reason why an incident or event occurred that identifies a correctable failure(s) in management systems. There is typically more than one root cause for every incident or event. Also referred to as root cause or underlying cause.
Management of Change Process	Documentation of the steps involved to ensure the safe startup and operation of a new facility
Consequence	An event or chain of events that result from the release of a hazard.
Evidence	Data on which the investigation team will rely for subsequent analysis, testing, reconstruction, corroboration, and conclusions.
Immediate Cause (IC)	A cause where a substandard act was performed or a substandard condition existed. Also referred to as direct cause.
Lessons Learned	The application of knowledge gained from past incidents, near misses, or other events in association with the goal of preventing similar events from occurring in the future.
Mitigative Barrier	Barriers to the right of the event (after it has happened). They reduce the severity of the consequence event. Mitigation barriers are sometimes referred to as "contingencies" or "recovery measures."
Preventive Barrier	Barriers to the left of the event (before it has happened). They reduce the likelihood of the event. Preventive barriers are sometimes referred to as "controls."
Root Cause	A fundamental, underlying, system-related reason why an incident or event occurred that identifies a correctable failure(s) in management systems. There is typically more than one root cause for every incident. Also referred to as underlying cause.
Root Cause Failure Analysis	A formal investigation method that attempts to identify and address the management system failures that led to an incident or event. These root causes often are the causes, or potential causes, of other seemingly unrelated events. Identifies the underlying reasons the event was able to occur so that workable corrective actions can be implemented to help prevent recurrence of the event (or occurrence of similar events).
Threat	A possible cause that will potentially release a hazard and produce a top event.
Top Event	Chosen credible scenario that is associated with the release of the hazard.

Acronym	Meaning
ACAO	Amended Corrective Action Order
AGT	Algonquin Gas Transmission, LLC
AWG	American Wire Gauge
BC	Basic Cause

Acronym	Meaning
BSCAT	Barrier-based Systematic Causal Analysis Technique
DNV GL	DNV GL USA, Inc.
E/I	Electrical and Instrumentation
ESD	Emergency Shutdown
FAT	Factory Acceptance Testing
HMI	Human Machine Interface
IC	Immediate Cause
IMS	Integrated Management System
I/O	Inputs and Outputs
ISRS	International Sustainability Rating System
LED	Light Emitting Diode
MCC	Motor Control Center
MOC	Management of Change
NTP	Notice to Proceed
MSCF	Thousand standard cubic feet
OIU	Operator Interface Unit
PHMSA	Pipeline and Hazardous Materials Safety Administration
PLC	Programmable Logic Controller
PSSR	Pre-startup Safety Review
QA/QC	Quality Assurance/Quality Control
RCFA	Root Cause Failure Analysis
SCADA	Supervisory Control and Data Acquisition
SCAT	Systematic Causal Analysis Technique
UST	US Transmission

1 INTRODUCTION

DNV GL USA, Inc. (DNV GL) performed a root cause failure analysis (RCFA) of an unplanned event that triggered the emergency shutdown (ESD) system and subsequent blowdown at the Algonquin Gas Transmission, LLC (AGT)[2] Weymouth Compressor Station in Weymouth, Massachusetts, on September 30, 2020. The ESD system is designed to monitor various safety and operating parameters, isolate and depressurize the system, placing the station into a safe state. In this instance, depressurization resulted in a release of approximately 195,000 cubic feet (195 mscf) of natural gas. The Amended Corrective Action Order (ACAO) issued to AGT by the Pipeline and Hazardous Materials Safety Administration (PHMSA) requested that an independent, third party conduct the RCFA, for which DNV GL was subsequently approved by PHMSA.

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The release reportedly occurred at 683 psig during commissioning. Commissioning activities are undertaken to ensure tightness and verify all equipment for operational readiness.

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The objectives of the RCFA were to identify the most probable direct (immediate) cause and root cause(s) of the ESD that resulted in the blowdown event at the Weymouth Compressor Station, and document the decision-making process and the factors contributing to the event, including findings and lessons learned. DNV GL's work involved reviewing documentation and conducting interviews associated with the design, installation, service, and operational history of the station, including associated procedures and practices. These activities were the main inputs to four (4) causal analysis workshops, facilitated by DNV GL, that utilized the BSCAT™ to document and evaluate the effectiveness of barriers in place to prevent the immediate cause that led to the ESD event. The team discussed recommended improvements to lower the likelihood of a similar event from occurring in the future.

The conclusions of this RCFA are based on findings from the document review, site visit to the Weymouth Compressor Station, interviews, and BSCAT™ workshops facilitated by DNV GL. DNV GL reserves the right to modify or supplement the conclusions represented herein should new information become available.

[2] Algonquin Gas Transmission, LLC is a subsidiary of Enbridge Inc.

2 INVESTIGATION PROCESS

DNV GL's investigation process began with initial familiarization of the event through telephone calls and initial document review. Upon arrival in Massachusetts, the DNV GL team reviewed documentation and conducted interviews to gain further understanding of the sequence of events. As the investigation progressed, additional documents were provided by AGT, and DNV GL conducted follow-up interviews to ensure adequate information was available to determine the preliminary direct (immediate) cause. The team utilized the knowledge gained in the early steps of the process to conduct causal analysis sessions, using DNV GL's BSCAT™ methodology, and identify recommended improvements. Figure 1 provides a schematic overview of the investigative process utilized for this investigation.

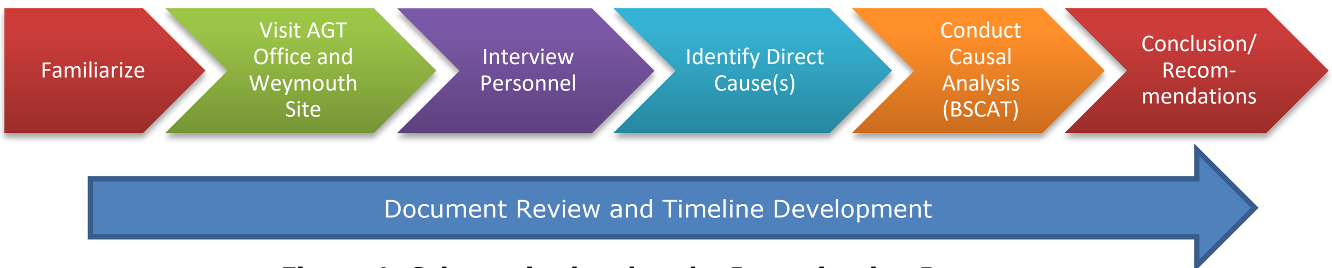

Figure 1: Schematic showing the Investigation Process

2.1 DNV GL Mobilization and Initial Information Gathering

Many of the interviews and initial document review were performed at the AGT Waltham office before the DNV GL team visited the Weymouth Compressor Station, which allowed the team to be prepared with questions for site personnel and specific areas of interest during the site activities. At a meeting on October 22, 2020, regarding the ESD event, AGT reported to PHMSA that the Federal Bureau of Investigation (FBI) was satisfied with AGT's determination that no cyberintrusion event occurred, in connection with the ESD event. As a result of these discussions between AGT and PHMSA, PHMSA indicated to AGT that cyber security was not necessary to include within DNV GL's scope of review of causal factors.

2.1.1 Familiarization

At the start of the investigation, DNV GL reviewed documentation provided by AGT related to the September 30, 2020 event. DNV GL then conducted interviews, both onsite and via telephone, with key AGT personnel and contractors during the week of October 12, 2020 to gain insight into activities and observations made before, during, and after the ESD event, as well as clarify questions related to the reviewed documentation. The documents and interviews became the main inputs to BSCAT workshops. The interviews involved seven (7) AGT employees and seven (7) contractors in the following roles:

- Functional Coordinator
- Area Supervisor
- Electrical and Instrumentation (E/I) Technician Specialist
- Electrical and Instrumentation (E/I) Technician
- Area Safety Lead
- Site Safety Inspector
- Electrical Inspector
- Project Engineer
- Commissioning Lead
- Electrical Superintendent
- Electrical Engineers
- AGT Investigation Team

2.1.2 Document Review

The DNV GL investigation team was supplied drawings, reports, procedures, and data logs and briefed by AGT project engineers on the Weymouth Compressor Station site. The team was also briefed on the ESD system design philosophy (ESD operation including triggering mechanisms) and provided answers to initial questions from the investigation team. Additional documentation was provided by AGT throughout the investigation, as requested by the DNV GL team and/or as AGT identified additional relevant documentation.

Following the briefing, the DNV GL investigation team reviewed and discussed the effect and manifestations of potential failure modes in the ESD system with the AGT investigation team. This exercise was used to create a preliminary list of potential immediate causes that could initiate an ESD event.

2.1.3 Interviews

Personnel relevant to the event were interviewed by DNV GL during the site visit. Personnel who were not physically present on site were interviewed over the phone.

The DNV GL team asked each interviewee to describe his or her observations the day of the event, in their own words. Follow-up questions were asked to clarify the following details:

- How were you made aware of the event?
- Where were you during the event?
- What did you observe during and after the event?
- Describe your involvement after the event.

Collating the information from the interviews and data logs, the DNV GL investigators were able to corroborate and confirm observations and details from different perspectives, which aided in generating a timeline and substantiating key timeline events.

If the team encountered information gaps or uncertainties related to specific information gathered from an interview or document review, follow-up interviews were conducted. Also, in some cases, additional interviews were conducted to gain additional insight or to seek further clarity.

2.1.4 Weymouth Site Visit

The DNV GL team was given a safety briefing at the AGT Waltham office prior to departing for Weymouth, where the DNV GL investigation team was given a tour of the Weymouth Compressor Station site by AGT with focus on the ESD system components, including the following:

- ESD Pushbuttons
- ESD Driving and Pilot Pressure Systems
- ESD Panel
- Batteries and Power distribution

The investigation team was provided full access to the site by AGT.

2.2 Timeline of the Event

The interviews, as well as AGT-provided information, were used to create two timelines: the project overview timeline shown in Figure 2 and the event timeline shown in Figure 3. In some cases, specific times were available, and in cases where a specific time was not available, an approximate time[3] was used.

Based on the timeline, the most likely sequence of events was established and areas for further investigation were identified.

2.2.1 Activities Leading to the Event

Figure 2 provides an overview of key dates for the Weymouth Compressor Station Project. The Weymouth Compressor Station was initially designed in February 2015 as a part of the Atlantic Bridge Project to provide additional natural gas pipeline capacity to the New England states and the Canadian Maritime provinces. The compressor station is located in northern Weymouth, Massachusetts, a city located south of Boston. The construction drawings were issued in July 2016 and construction on the project commenced until January 2017, when the project timeline was unexpectedly extended, and equipment was put into long-term storage. The Federal Energy Regulatory Commission (FERC) issued the Notice to Proceed (NTP) in November of 2019, and construction restarted in December 2019 with the intention to place the station into service in October 2020. From July to September various commissioning activities were undertaken at the site, including a quality assurance (QA) inspection on September 5, 2020.

Figure 3 provides a timeline of activities leading up to and following the event. On the day of the event, September 30, 2020, there were many planned activities. The workday began with safety briefings and continued according to the plans for construction, install, and updates. At approximately 8:00 a.m., numerous activities occurred concurrently: a contractor pre-job / kickoff meeting in the motor control center (MCC) room, a hot work permit was issued, resources for work were identified, setup for project work continued from earlier work (lights, cathodic protection, and heat tracing), startup strainer removal work, MCC incoming breaker work, transformer removal and disconnect work, civil work and construction, ground compacting, fencing work, and building punch-list work.

At approximately 10:15 a.m., an ESD at the compressor station resulted in the controlled release of 195 mscf of natural gas through a 30-foot tall vent stack. This ESD, and subsequent venting, was the focus of the investigation. The ESD system is designed to protect the public, employees, and critical pipeline and facility components from abnormal operations by safely releasing natural gas to a remote vent stack, away from ignition sources and areas where the gas may cause harm. In this case, the ESD and blowdown were activated, and the system worked as intended.

During the event, station personnel audibly detected venting from the surge reliever and observed the human machine interface (HMI) and ESD programmable logic controller (PLC) rebooting. Immediately afterward, the compressor building was vacated in accordance with response procedures, and the station was blocked in (shut in) to 1 psig natural gas pressure.

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[3] Timeline events with approximate times are *italicized*.

The SCADA data show that at 10:21 a.m. and 10:35 a.m., the ESD Alarm and ESD Fail Alarm, respectively, were tripped for the station. At 10:29 a.m., a call was placed to notify the Westwood Area Manager. At 10:32 a.m., a call was placed to notify the Regional area environmental representative. At 10:35 a.m., a call was made to notify Environmental Permitting. All work was stopped onsite at 10:35 a.m. Initial trouble shooting of the ESD panel started at 10:35 a.m. After initial troubleshooting, planned activities for the day continued, because they were not affected by the ESD. The system was re-energized to 129 V_{DC} between 7:00 p.m. and 8:00 p.m. on the 30th.

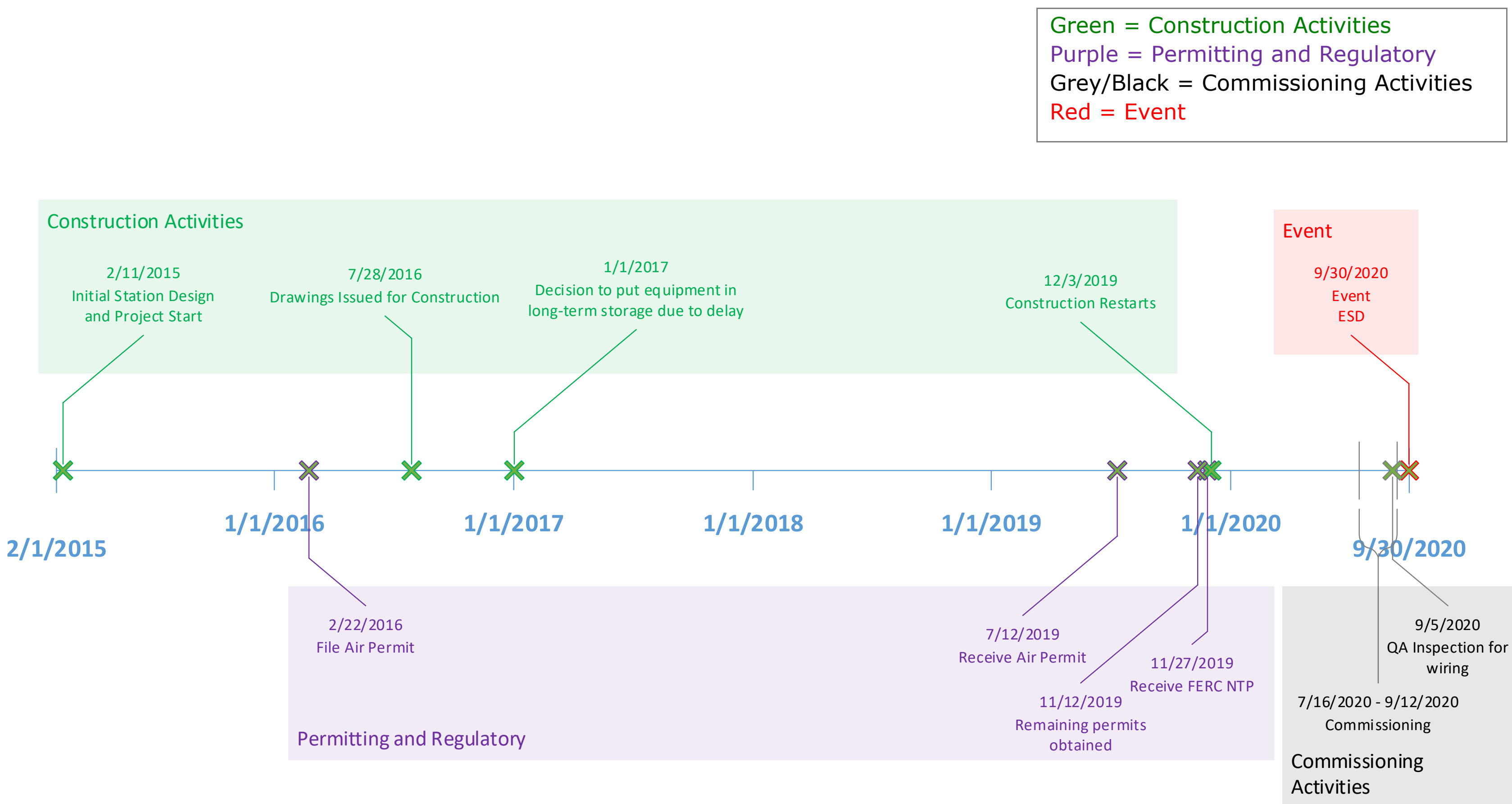


Figure 2: Timeline of the Weymouth Compressor Station Project.

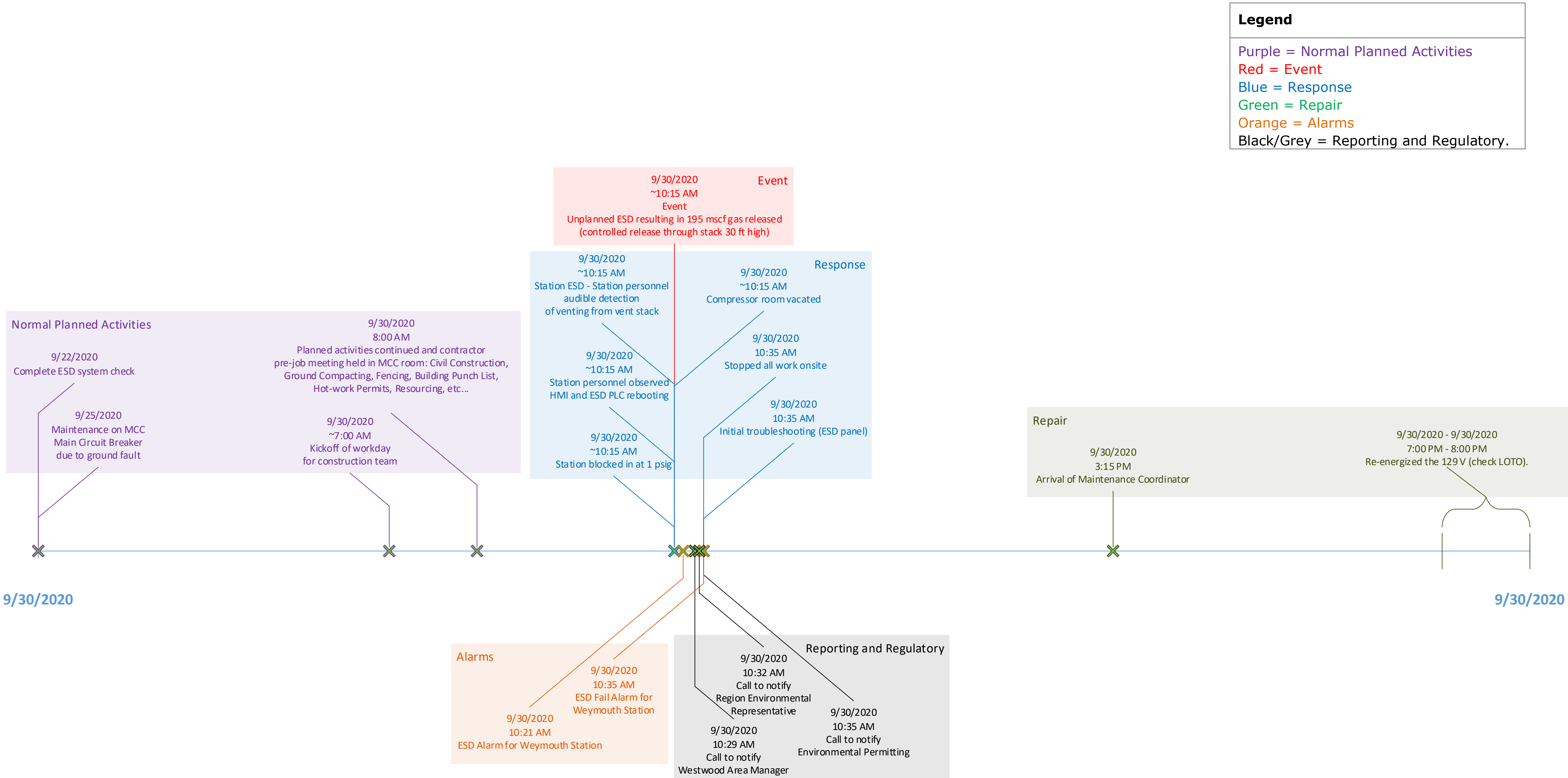


Figure 3: Timeline showing key events/activities on the day of the ESD event, September 30, 2020.

3 IMMEDIATE / DIRECT CAUSE

While onsite, DNV GL personnel evaluated the systems and components that may have failed, triggering the ESD event. As part of the review, observations were made suggesting that a power interruption may have contributed to the event. Figure 4 is a schematic showing the power distribution to the 129 V_{DC} system that supplies power to the ESD panel at Weymouth. The ESD panel sits on a 129 V_{DC} bus that provides power to ten circuits.

Several observations were made based on the interviews and system review, and in some cases, data logs were used to substantiate these observations. Table 1 summarizes the observations and data log entries.

Redacted Confidential Information per FOIA Exemption 4;7(F)

[redacted]

Figure 4: Weymouth Power Distribution

Several observations were made based on the interviews and system review, and in some cases, data logs were used to substantiate the observations. Table 1 summarizes the observations and data log entries.

Table 1: Summary of Observations and Data logs

Observations and Logs	Description	Verification
Station PLC operational	The Station PLC was operational before, during and after the event with no errors reported. This indicates the Station PLC did not lose power during the event and that the main 129 V_{DC} bus was powered.	Data logs and observations
Station HMI Operator Interface Unit (OIU) was frozen (unresponsive)	Following the event, the Station HMI (OIU) was observed in a frozen state. This indicates a communication issue with either the Station HMI or ESD HMI and indicates that the Station HMI did not reboot.	Observations
Unit 1 strobe lights ON	Several personnel observed Unit 1 strobe lights. This indicates that the main 129 V_{DC} was powered.	Observations
ESD HMI rebooting	Following the event, personnel observed the ESD HMI rebooting.	Observations
ESD PLC reporting fault	Following the event, the ESD PLC reported errors in data logs.	Data logs
ESD Pilot and Power Gas integrity verified	Following the event, the Pilot and Power gas were inspected, tested, and verified to be free of any faults or leaks.	Inspection and verification
ESD fault alarms during event	Following the event, the ESD PLC reported an error by Light Emitting Diode (LED) indicators in ESD panel door.	Data logs and observations
Valve activations reported	Data logs report movement and positions of valves before, during and after the event.	Data logs
MCC Unmanned	No personnel were present or observed in the MCC room (location of circuit breakers).	Observations
ESD Panel closed	The ESD panel doors were closed, and there were no personnel working on panel internal components.	Observations

3.1 Identification of Direct Cause

Following extensive team meetings to review the intended design and potential failure modes, the possible paths to trigger an ESD event were organized into three main categories. These categories are described in the following list, with each category having two or more potential direct causes:

1. Designed operation (D) – Initiation of ESD with a designed mechanism
   - D1 Pushbutton activation (electrical)
   - D2 Manual open pilot gas blowdown valve (manual ESD)
   - D3 Operating the surge reliever pressure switch
   - D4 PLC initiated ESD from Fire and Gas detection logic
2. Faults (F) – Initiation of ESD due to technical faults
   - F1 Loss of containment from pilot gas lines (surge reliever or gas lines)
   - F2 Open circuit in the pushbutton daisy chain
   - F3 Complete loss of 129 V_{DC} (Battery and Charger ⇦ 480 V_{AC} ⇦ 13.8 kV_{AC})
   - F4 Loss of 129 V_{DC} power to ESD Panel
   - F5 ESD PLC spurious operation
   - F6 Loss of 24 V_{DC} in ESD Panel, which powers surge relievers
3. Unplanned operation (U) – Initiation of ESD by unintended human activity
   - U1 ESD Panel Circuit breaker activation
   - U2 ESD PLC Circuit fuse disconnect

Each potential direct cause was analyzed according to its resulting system response in data logs and observable system response, as detailed in Figure 5. In the figure, green indicates that the potential direct cause could trigger a response or SCADA log entry, while blue indicates the cause cannot trigger the response observed or log entry. These expected symptoms/system response were then compared to the actual observations and log entries from the time of the event to test consistency with the event being investigated.

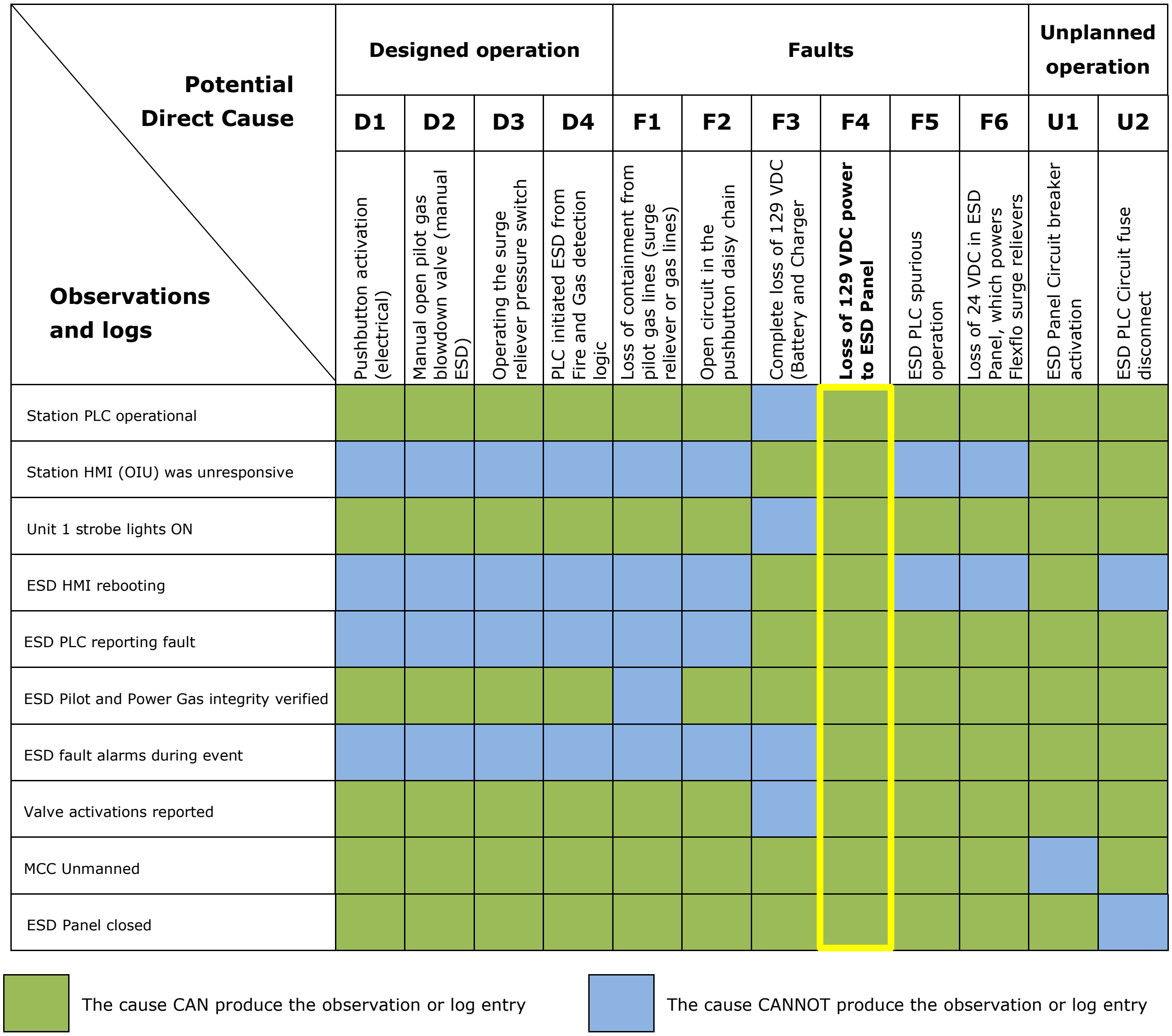


Figure 5: Potential Direct Cause Determination

The columns, corresponding to potential direct causes, containing a blue square were excluded as direct causes of the event. For example, D1 (Pushbutton activation) will not result in the Station HMI being frozen nor will it trigger ESD HMI reboot, hence it can be determined that the ESD was ***not*** triggered by D1 (ESD Pushbutton activation). This was further substantiated by the discovery that no pushbuttons were in a pushed-in state (requires manual pull reset), and all circuitry was tested and found to be according to design with no errors after the event.

The analysis shown in Figure 5 reveals only one column with all green squares, indicating that there is only one potential direct cause that will generate the symptoms that match all of the observations and data logs:

- *F4 - Loss of 129 V_{DC} power to ESD Panel*, which is indicated by the yellow framed box in Figure 5.

Loss of 129 V_{DC} power to the ESD Panel may be caused by an interruption of the current path (e.g., open circuit) to any component, connection, or wiring in this 129 V_{DC} power circuit.

Prior to DNV GL's onsite activities, two circuit breakers were removed by AGT, and the cable between the two breakers was removed during DNV GL's site visit. All were preserved and retained by AGT for further testing. These components were subjected to inspection and functional static testing. All were found to be without any damage and functioned according to design specifications;[4] therefore, a specific component failure was not identified, and the specific trigger for loss of 129 V_{DC} is indeterminant. As such, all potential causes for loss of 129 V_{DC} were considered as the immediate cause and then used as the basis for the BSCAT™ process. These immediate causes included:

1. Open circuit resulting from faulty equipment, loose connection, or damage during shipping.
2. Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction. Scheduled ground compaction activities were occurring at the compressor station at the time of the event. During interviews and while DNV GL was on site, the vibrations caused by this activity were described as unusually strong, significantly beyond normal operational activities.

[4] The components were not tested under mechanical dynamic loading conditions, such as vibration, because those conditions could not be easily replicated.

4 ROOT CAUSE ANALYSIS WITH BSCAT™

DNV GL used a systematic root cause analysis methodology to investigate the underlying weaknesses in the management system (i.e., procedures and processes) related to the September 30, 2020 event. When investigating operational incidents and undesired events, the use of a systematic approach helps ensure that the underlying weaknesses in the management system are identified and addressed. Without a systematic approach, too much reliance may be placed on the specific knowledge, experience and personal viewpoint of the person carrying out the investigation, which may result in different investigators identifying different causes. An unstructured approach can also result in inappropriately blaming either the equipment or the person without consideration of the underlying, system related root causes. By identifying opportunities for improvement in the management systems, more effective solutions can be developed that will result in more effective barriers for the prevention of recurrences.

4.1.1 BSCAT™ Methodology

DNV GL's barrier-based systematic causal analysis technique (BSCAT™) is a well-established, industry accepted methodology for investigating accidents and identifying root causes. The predecessor, SCAT, was originally developed in the 1980s as part of DNV GL's International Safety Rating System (ISRS™) [1]. The methodology has been used for decades by DNV GL and client companies around the world to evaluate many serious incidents across different industries.

BowTie diagrams are used to identify the barriers that are in place to prevent threats from escalating into top events and the barriers that are in place to mitigate consequences following a top event. This analysis can be performed before an event to help assess the barriers that are in place and their current state. BowTies can also be created following an event to analyze the system's barriers at the time of the event.

Systematic Causal Analysis Technique (SCAT™) is a root cause analysis approach that uses standardized causation descriptions to describe the immediate (direct) and basic causes helping incident investigators to identify weak areas of the management system. The standard causation descriptions help to categorize commonalities that can be tracked to prioritize the areas of the management system that are related to root causes of the event.

BSCAT™ applies the SCAT™ model to each barrier as opposed to the event as a whole. This method results in a review of the effectiveness of the individual barriers identified in the assessment. Figure 6 depicts the basic approach of how BSCAT™ is applied to address the controls prior to an event and after the event has occurred, and it also shows a comparison of the Traditional SCAT™ methodology compared to the BSCAT™ methodology. Note that the terms "control" and "barrier" are used interchangeably in this process.

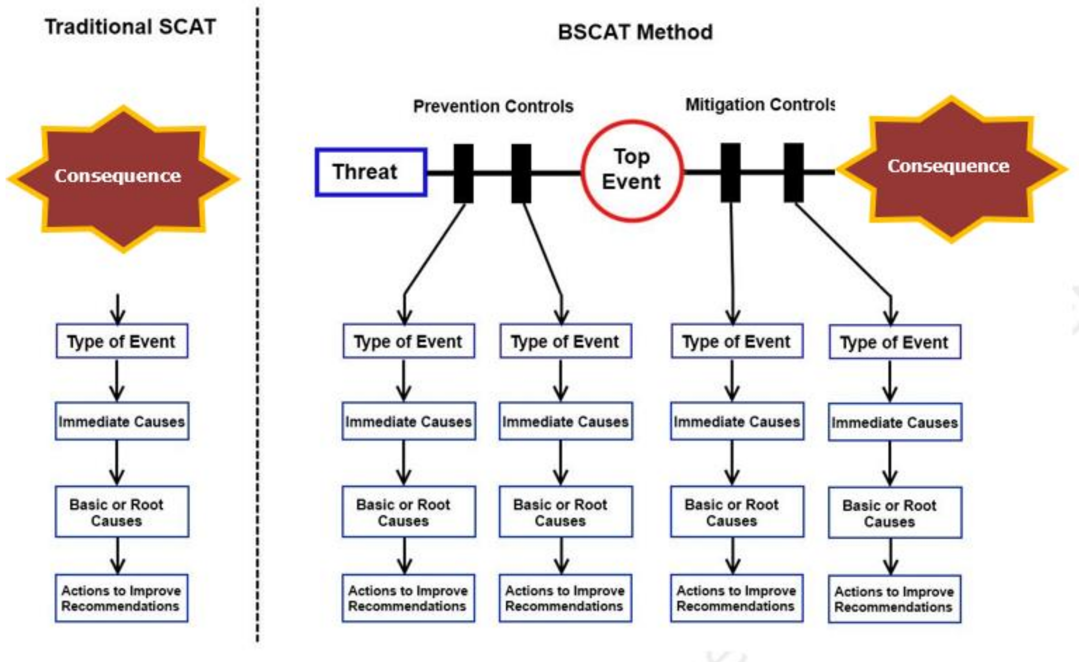


Figure 6: Comparison of Traditional SCAT and BSCAT Methodologies.

The BSCAT™ process involves the following steps:

a) Evidence Capture and Review – Collecting information pertaining to the event through interviews of the people involved and reviews of documents related to the event. The majority of the evidence for this investigation was obtained through interviews and document review.

b) Timeline Development – Creation of a timeline of events leading up to and during the event. The timeline was developed with AGT from the knowledge of site personnel.

c) Barrier Identification – A BowTie diagram is created for the threat that escalated to the main event. The barriers in place, as well as those that could have been, are identified at this time.

d) Barrier Type– The types of barriers (e.g., administrative control, design, etc.) are determined with the team.

e) Causal Analysis – The SCAT™ process is then applied to each barrier identified as failed, missing, or insufficient.

4.1.2 BSCAT™ Workshop Team

DNV GL facilitated four BSCAT sessions by remote call-in with the AGT team on the following dates:

- November 13, 2020
- November 30, 2020
- December 1, 2020
- December 3, 2020

A balanced, cross-functional team was assembled for the BSCAT ™ workshop, which included individuals with extensive knowledge of the Weymouth Compressor Station. The DNV GL facilitator of the workshop has had formal training in conducting root cause analyses using the BSCAT™ methodology; some AGT team members have also had training in the methodology.

During the BSCAT™ sessions, the team referred to documents, data, and interview information from earlier stages of the investigation to discuss the scenarios and status of each barrier.

4.1.3 BowTie Diagram Development

In the BowTie diagram (Figure 7), the undesired event being investigated - the top event - is shown in the center as the "knot." Threats that can, or did, lead to the top event are shown to the left-hand side of the knot. The possible consequences are shown on the right-hand-side of the top event.

Threats, as well as the consequences, can be controlled with the use of "barriers." Barriers are shown on the BowTie diagram as blocks between the threats and the top event (i.e., preventive barriers) and between the top event and the consequences (i.e., mitigation barriers). Barriers can be physical barriers, such as hardware, or procedural barriers, such as procedures and plans.

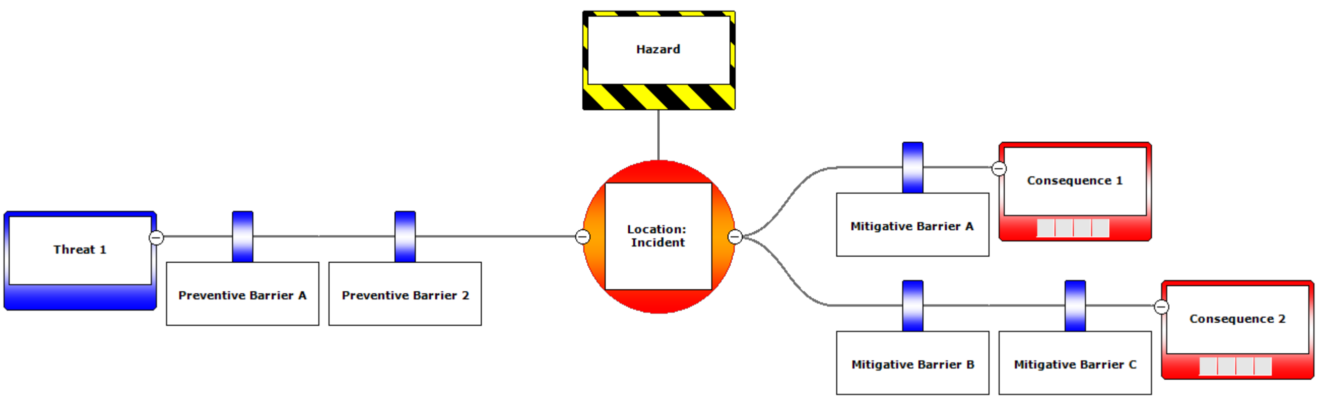


Figure 7: Typical BowTie Diagram.

4.1.4 BSCAT Legend

To better understand the discussion that follows, Figure 8 presents a legend showing symbols used in the BSCAT™ analysis. This figure shows the Initiating Event / Cause in the blue box to the left side – this starts the event sequence. The red and orange box in the center, the Top Event, represents the time when a loss of control occurs – for this investigation the Top Event is selected as the unplanned ESD that resulted in a controlled gas release. To each side of the Top Event are barriers that should have been able to prevent the Top Event from occurring (on the left side of the diagram) or mitigate the event (to the right side of the Top Event).

Four barrier symbols are displayed in Figure 8:

1. Missing: should/could have been present but was missing at the time of the event;
2. Failed: failed in its function during the time of the event;
3. Insufficient: functioned in the event but had some weaknesses or only partially worked OR in place but not appropriate to prevent undesired events in the future;
4. Effective: worked as expected and was effective.

For each barrier, the Immediate (Direct) Causes, Basic (Root) Causes and Recommendations are summarized. The figure below provides an overview of the barriers and sub-barriers evaluated for the September 30, 2020 event.

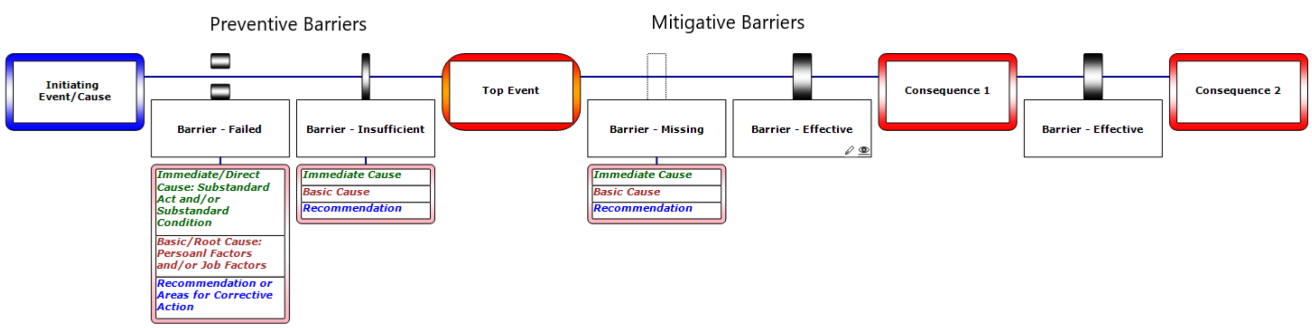


Figure 8: BSCAT™ Diagram Legend.

4.1.5 SCAT™ Analysis

For each barrier found to be missing, failed, or insufficient, the SCAT™ process was applied to determine the immediate and basic causes of the barriers' failure or inadequacy. An assessment of the primary barriers as they pertained to the Weymouth ESD event is provided in Section 5. By evaluating all potential barriers individually, and the root causes of why those barriers were insufficient or missing, BSCAT™ provides a broad view of the event and associated areas of improvement for the management system. This approach provides AGT with the opportunity to make improvements that are specifically targeted to preventing similar events across the organization.

5 BARRIER ANALYSIS

The BSCAT™ methodology was applied to determine the direct and basic causes of each identified barriers' failure or inadequacy. The direct cause was determined to be an open circuit, resulting in loss of 129 V_{DC} power to the ESD panel (F4 in Figure 5).

The team determined that there were two scenarios that have different barriers; therefore, the final results of the evaluation are grouped into two "branches" of the BSCAT™ diagram.

1. **Open circuit resulting from faulty equipment, loose connection, or damage during shipping**: The BSCAT team discussed the possible contributing factors to the open circuit and identified the barriers for each scenario. The barriers were discussed and evaluated for their effectiveness during the event, as outlined in Sections 5.1.1 and 5.1.2.

2. **Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction**: The compaction that was ongoing at the time of the event is not typically done while a facility is in operation. This activity resulted in an unusually high magnitude of vibration. It is possible that a tight connection that meets requirements under normal circumstances could not withstand the vibration induced from the ground compaction activities, resulting in an open circuit and subsequent ESD. It is also possible that a loose connection for any of the reasons noted in the overall open circuit scenario was interrupted by the ground compaction. To account for barriers that may be specific for this activity, large-scale ground compaction activity being done as part of construction was separated into its own arm of the BSCAT™ diagram.

The conclusions of this investigation are based on an assessment of the preventive barriers (intended to reduce the likelihood of an event) illustrated in the simplified diagram depicted in Figure 9, and discussed in Section 5.1. The complete BSCAT™ diagram, which can be found in Appendix A, includes the full causation for each barrier that contributed to the event.

It should be noted that the BSCAT™ terminology for each immediate cause and basic cause, e.g., "inadequate," "improper," "lack of," or "failure to," is standardized for use across all industries. For this reason, additional information is provided in the diagram in the appendix to expand on the reasons for the barriers performing in an ineffective manner. Section 5.1 includes additional information regarding each of the barriers analyzed as part of this investigation.

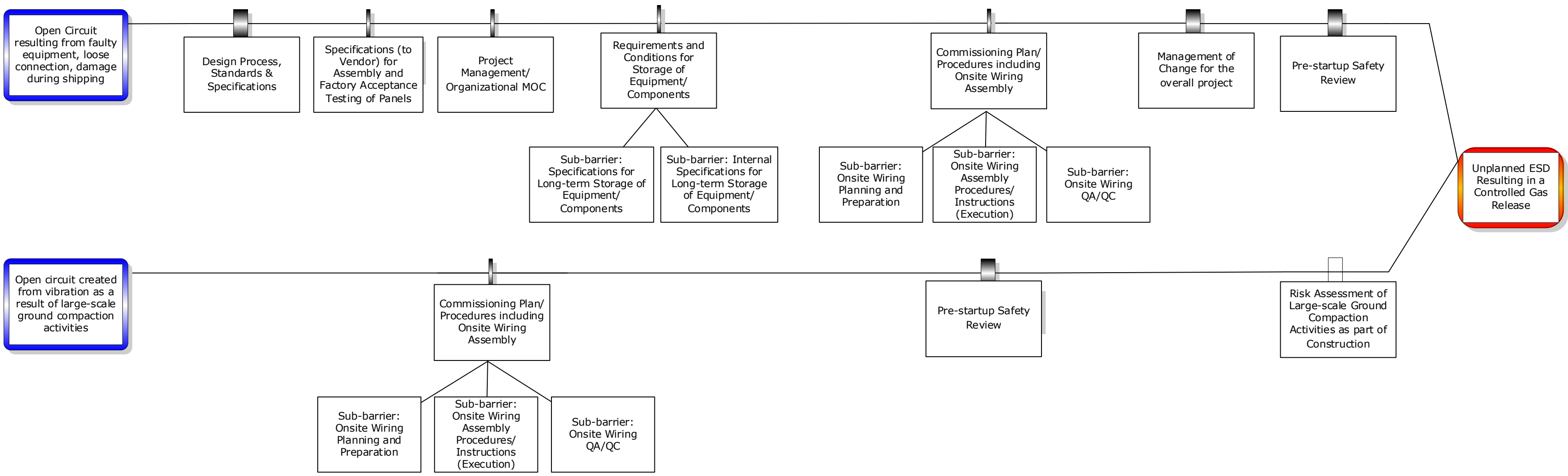


Figure 9: Simplified BSCAT™ Diagram showing the barriers evaluated for the ESD Event.

5.1 Preventive Barriers

The preventive barriers and their sub-barriers are detailed in the following sections. During the BSCAT™ workshops, the team members identified each of the barriers that were in place at the time of the event as well as those that could have been in place to prevent the event from occurring. The team identified causal barriers, which are those whose failure or inadequacy contributed to the event, as well as non-causal barriers, which were effective during the event or did not contribute to the event.

For the **open circuit resulting from faulty equipment, loose connection, or damage during shipping** (referred to as the "open circuit" scenario), five (5) barriers were determined to be non-causal to the event, and two (2) barriers, highlighted in yellow, were determined to contribute to the scenario, as shown in Table 2.

For the **open circuit created from vibration as a result of large-scale ground compaction activities as part of construction** (referred to as the large-scale compaction scenario), one (1) barrier, the Pre-Startup Safety Review (PSSR), was determined to be non-causal in the case of the specific open circuit created, and two (2) barriers, highlighted in yellow, were determined to contribute to the scenario.

The discussion for each of the causal barriers in Sections 5.1.1 and 5.1.3 includes a table outlining the barrier's status for the event, as well as the immediate and basic causes (and BSCAT™ coding) of their failures. It should be noted that the BSCAT™ coding and wording is intended for general use; therefore, there is additional information in the table, as well as the section's discussion, to further explain each barrier's status.

Recommendations for improvement pertaining to insufficient and missing barriers are noted at the end of each table. There were, however, opportunities for improvement identified during the analysis of the barriers that were not deemed causal to the event. These observations are presented in the following sections.

Table 2: Listing of Preventive Barriers for the two Scenarios Evaluated during BSCAT Sessions

Preventive Barriers: Open circuit resulting from faulty equipment, loose connection, or damage during shipping	**Preventive Barriers:** Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction
1. Design Process, Standards and Specifications 2. Specifications (to vendor) for Assembly and Factory Acceptance Testing of Panels 3. Project Management / Organizational Management of Change (MOC) 4. Requirements and Conditions for Storage of Equipment/Components 5. Commissioning Plan/Procedures including Onsite Wiring Assembly 6. Management of Change for the Overall Project 7. Pre-startup Safety Review	1. Commissioning Plan/Procedures including Onsite Wiring Assembly 2. Pre-startup Safety Review 3. Risk Assessment of Large-scale Ground Compaction

5.1.1 Open Circuit resulting from Faulty Equipment, Loose Connection, or Damage during Shipping: Non-causal Barriers

As shown in Table 2, a total of seven (7) preventive barriers were identified for the open circuit scenario. The following five (5) barriers were identified by the team as non-causal to the September 30, 2020 event:

1. **AGT's Design Process, Standards and Specifications**

   In this case, the Design Process and the associated standards and specifications barrier did not fail; the system was designed, built and tested with specifications that are fit for purpose and successfully used in many previous projects; therefore, there is no analysis of the barrier and no other specific design processes, standards and specifications were reviewed during the investigation.

   AGT's design standards call for use of ferrules to avoid stray strands of wire and is applied for smaller wire sizes where stray strands are more likely to occur during installation. The standards and specifications were appropriately applied; however, the barrier pertaining to the Commissioning Plan and Procedures, discussed below, provides additional analysis of the application of the ferrules.

2. **Specifications (to vendor) for Assembly and Factory Acceptance Testing (FAT) of Panels**

   The Factory Acceptance Test (FAT) is a process that evaluates equipment built by a vendor during and/or after the assembly process. In the case of this event, the purpose of the FAT, which was performed on August 22 and 23, 2016, was to verify that the station control and electrical equipment was built, and operating, in accordance with design specifications after fabrication of the control panel was complete. The FAT performed for the Weymouth station control system ensured that the inputs and outputs (I/O) of components and controls are working properly; the full wiring assembly was tested onsite at the time of installation. For this reason, FAT was not found to be a contributing factor in the event, because the corresponding electrical connections would not result in all the observations listed in Table 1.

3. **Project Management / Organizational MOC**

   The team determined that this barrier did not fail and was not a direct contributor to this event. The Weymouth project had multiple project engineers and changes in project personnel. A formal, documented process of handover from one project team member to another is not in place; however, the AGT team noted that there is good communication within the project. By incorporating a formal process to manage organizational changes within projects and handover to new personnel, continuity can be ensured.

4. **Management of Change for the Overall Project**

   A MOC was performed for the project, with the scope of increasing compression capability to effectively serve customers. The MOC form was being used and was executed (incorporated all necessary signatures) prior to the event. The September 30, 2020, event occurred during the MOC process, prior to the change being completed.

The overall startup process is guided by the *Integrated Management System (IMS) Asset Management of Change-* document for the company's US Transmission business unit. This outlines the MOC process and documents the steps involved to ensure the safe startup and operation of the facility.

5. **Pre-startup Safety Review (PSSR)**
   The PSSR is a systematic and thorough check of a process prior to the introduction of first gas and culminating with handover to Operations. The PSSR confirms the following: construction and equipment are in accordance with design specifications; safety, operating, maintenance, and emergency procedures are in place and are adequate; a process hazard analysis has been performed for new facilities and recommendations have been resolved or implemented before startup, and modified facilities meet the management of change requirements; and training of each employee involved in operating a process has been completed. [2]

   The PSSR was determined to have been effective up to the point of the event, which occurred before the final stage of the PSSR. Although the PSSR is intended to confirm the asset is ready for operation, it is not intended to re-check everything that was done as part of commissioning QC. AGT's PSSR process is carried out essentially in three stages. One group of tasks is done before first gas is introduced. The second group is done after commissioning, and additional PSSR tasks are done before handover to Operations.

5.1.2 Open Circuit resulting from Faulty Equipment, Loose Connection, or Damage during Shipping: Causal Barriers

As shown in Table 2, a total of three (3) preventive barriers were determined to be causal for the general open circuit scenario, meaning they were either deemed to be "missing" or "insufficient," as defined in the BSCAT™ legend. The following subsections describe the barriers determined to be causal to the September 30, 2020 event.

5.1.2.1 Requirements and Conditions for Storage of Electrical Equipment and Components

The barrier associated with requirements and conditions under which electrical equipment and components should be stored was divided into two sub-barriers: the verifiable communication with vendor for unique handling and storage of components and the AGT internal specifications for long-term storage of components. Neither barrier failed as a whole; however, both were determined to be insufficient to be able to prevent damage or deterioration of electrical equipment and components in the future.

There are protective materials and lubricants, e.g., grease, corrosion protection, etc., that, if not designed for long-term storage, can become deteriorated or ineffective. In the case of this event, the material applied to the terminals had hardened during the period of storage, which can hinder the free movement of the terminal screws. Additionally, there was evidence of deteriorated components when unwrapping the breaker panel.

Table 3 summarizes the barrier and sub-barriers associated with storage of electrical components and the factors that contributed to this event.

Table 3: Analysis of Barrier: Requirements and Conditions for Storage of Electrical Equipment and Components

Barrier: Requirements and Conditions for Storage of Electrical Equipment and Components	**Status for Event:** Insufficient
Sub-barrier: Verifiable Communication with Vendor for Unique Handling and Storage of Components	
Immediate Cause: IC18. *Failure to Identify Haz*ard Although there are panel specifications from AGT to the vendor for panel assembly, instructions were not specified for any unique storage requirements of components (conditions/environment for storage).	
Basic Cause: BC9.7. *Inadequate work/process planning* When the project was unexpectedly extended, there was no standard or work process that required consideration of long-term storage requirements and how to work with the vendor to ensure appropriate storage.	
Sub-barrier: Internal Specifications for Long-term Storage of Components	
Immediate Cause: IC18. *Failure to Identify Hazard* An internal specification for long-term storage is not in place. The breaker panel was stored at an offsite storage facility; however, potential hazards associated with the storage conditions were not evaluated.	
Basic Cause: BC9.7. *Inadequate Work/Process Planning*; **BC12.8.** *Improper Storage of Material* When the project was unexpectedly extended, there was no standard or work process that required consideration of long-term storage and how to work with the vendor to ensure appropriate storage. This facility was indoors but not in a climate-controlled environment, which resulted in some deterioration of components.	
Recommendation #1: Revise the internal procedures for Supply Chain Management pertaining to how AGT communicates with vendors regarding the requirements for safe packaging, transportation and storage (including long-term storage) of components and equipment for future projects and procurement. **Recommendation #2:** Develop a working document/standard for considerations to be made when future projects are delayed or put on hold for long periods of time, including such items as hazard identification, long-term storage of components, and communication with vendors.	

5.1.2.2 Commissioning Plan/Procedures (including Onsite Wiring Assembly)

The barrier associated with the commissioning plan and procedures was divided into three sub-barriers:

1) The planning and preparation for onsite wiring;
2) The execution of installation using wiring procedures and instructions;
3) The quality assurance/quality control (QA/QC) performed following initial installation.

The barrier did not fail as a whole; however, the barrier was determined to be insufficient to be able to prevent an event similar to this in the future.

During the investigation, the team discussed and observed that some terminal block connections in the ESD panel used ferrules that were not suitable for the specific terminal block. Design standards call for use of ferrules to avoid stray strands of wire; however, there were cases where the use of ferrules interfered with the full insertion of the wire into the terminal block, i.e., the ferrules were too large for the terminal block design.

Table 4 summarizes the commissioning plan barrier and sub-barriers and the factors that contributed to this event.

Table 4: Analysis of Barrier: Commissioning Plan/Procedures

Barrier: Commissioning Plan/Procedures	**Status for Event:** Insufficient
Sub-barrier: Onsite Wiring Planning & Preparation	
Planning, in the form of a checklist, was prepared in 2017 at the time of initial design. The wiring specifications for this project were for 14 AWG (24 V_{DC} power) and 16 AWG (for 4-20 mA signal) in the panel.	
Sub-barrier: Onsite Wiring Procedures/Instructions (Execution)	
Immediate Cause: IC9. *Using Incorrect/Improper Material* Ferrules are commonly used to secure wiring strands together. When the correct size and type are used, they help secure sections of stranded wire together, which can prevent short circuits. The ferrules provided by the contractor and used in this case were not the correct size for the terminal block.	
Basic Cause: BC5.6. *Lack of situational awareness/risk awareness*; **BC9.7**. *Inadequate work/process planning*; **BC17.2.** *Inadequate risk identification/evaluation in development of standard*; **BC17.4**. *Inadequate coordination with process design when developing standard* The inspection process did not identify that improperly sized/matched ferrules had been installed. According to AGT specification (Spec 27H2.17), wire sleeves should be from the same manufacturer as the associated terminal blocks; however, ferrule usage is not specified.	

Barrier: Commissioning Plan/Procedures	**Status for Event:** Insufficient
Sub-barrier: Onsite Wiring QA/QC	
Immediate Cause: IC23. *Inadequate Integrity of Equipment* The incorrect ferrule size was not identified during the QA inspection performed on September 5, 2020 (Commissioning Manual 8I1). Commissioning QA procedure is in place and a checklist was completed and signed off. The checks/inspections were done according to procedure, but the checklist (Commissioning Manual 8I1) does not include specifications for which method(s) are appropriate for verifying connections (e.g., physical integrity check/tug test, visual check, etc.). Electrician typically does a tug test after initial install. At commissioning, an inspector checks using Inspector's Manual (CS1.9), which only requires visual confirmation of connection. The commissioning visual inspection was performed by a vendor representative and AGT, but a physical tug test was not performed.	
Basic Cause: BC9.4. *Inadequate Standard* The inspection manual states that connections should be checked; however, final checks do not relate back to the specifications to ensure the appropriate types of checks are done, e.g., tug test. The Station Control Panel and ESD panel were checked as part of the MOC checklist, Step 6. Power connection from the 129 V_{DC} distribution bus for ESD - battery was checked, as well as at both panels, but the interconnecting power leads were not checked. The checklist only requires the inspector to check that the connections terminate at both ends.	
Recommendation #3: Improve wiring standards. Revise the internal standards regarding installation of ferrules and terminal blocks to ensure proper application of ferrules in the future. Ensure the standards and work processes specify the correct size and termination method(s) of the wire and terminal block. Ensure electrical standards/procedures for future projects require an integrity test of electrical connections (e.g., tug test, correct size and method of terminations, etc.) after installation and during commissioning.	

5.1.3 Open Circuit Created from Vibration as a result of Large-scale Ground Compaction Activities: Non-causal Barrier

As previously shown in Table 2, a total of three (3) preventive barriers were identified for the large-scale ground compaction scenario. The PSSR barrier was identified by the team to be non-causal to the September 30, 2020 event.

As with the open circuit scenario, the PSSR was determined to have been effective up to the point of the event, which occurred before the final stage of PSSR was complete. Although the PSSR is intended to confirm the asset is ready for operation, the PSSR is not intended to re-check everything that was done as part of commissioning QC.

5.1.4 Open Circuit Created from Vibration as a result of Large-scale Ground Compaction Activities: Causal Barriers

5.1.4.1 Commissioning Plan/Procedures including Onsite Wiring Assembly

This scenario shares a common barrier with the open circuit scenario resulting from faulty equipment, loose connection, or damage during shipping, specifically the barrier associated with the commissioning plan and procedures. For the large-scale ground compaction scenario, it was also determined that the barrier was “missing” or “insufficient,” as defined in the BSCAT^{TM} legend. The barrier did not fail as a whole; however, the barrier was determined to be insufficient for preventing an event similar to this in the future.

Table 5 summarizes the commissioning plan barrier and sub-barriers associated with storage of components and the factors that contributed to this event. The analysis determined that the immediate and basic causes for this barrier and sub barriers were the same as those identified in Table 4 for the open-circuit scenario discussed in Section 5.1.2.2.

Table 5: Analysis of Barrier: Commissioning Plan/Procedures including Onsite Wiring Assembly

Barrier: Commissioning Plan/Procedures	Status for Event: Insufficient
Sub-barrier: Onsite Wiring Planning & Preparation	
Planning, in the form of a checklist, was prepared in 2017 at the time of initial design. The wiring specifications for this project were for 14 AWG (24 V_{DC} power) and 16 AWG (for 4-20mA signal) in the panel.	
Sub-barrier: Onsite Wiring Procedures/Instructions (Execution)	
Immediate Cause: IC9. *Using Incorrect/Improper Material* Ferrules are commonly used to secure wiring strands together. When the correct size and type are used, they help secure sections of stranded wire together, which can prevent short circuits. The ferrules provided by the contractor and used in this case were not the correct size for the terminal block.	
Basic Cause: BC5.6. *Lack of situational awareness/risk awareness*; **BC9.7**. *Inadequate work/process planning*; **BC17.2.** *Inadequate risk identification/evaluation in development of standard*; **BC17.4**. *Inadequate coordination with process design when developing standard* The inspection process did not identify that improperly sized/matched ferrules had been installed. According to AGT specification (Spec 27H2.17), wire sleeves should be from the same manufacturer as the associated terminal blocks; however, ferrule usage is not specified.	

Barrier: Commissioning Plan/Procedures	Status for Event: Insufficient
Sub-barrier: Onsite Wiring QA/QC	
Immediate Cause: IC23. *Inadequate Integrity of Equipment* The incorrect ferrule size was not identified during the QA inspection performed on September 5, 2020 (Commissioning Manual 8I1). Commissioning QA procedure is in place and a checklist was completed and signed off. The checks/inspections were done according to procedure, but the checklist (Commissioning Manual 8I1) does not include specifications for which method(s) are appropriate for verifying connections (e.g., physical integrity check/tug test, visual check, etc.). Electrician typically does a tug test after initial install. At commissioning, an inspector checks using Inspector's Manual (CS1.9), which only requires visual confirmation of connection. The commissioning visual inspection was performed by a vendor representative and AGT, but a physical tug test was not performed.	
Basic Cause: BC9.4. *Inadequate Standard* The inspection manual states that connections should be checked; however, final checks do not relate back to the specifications to ensure the appropriate types of checks are done, e.g., tug test. The Station Control Panel and ESD panel were checked as part of the MOC checklist Step 6. Power connection from the 129 V_{DC} distribution bus for ESD - battery was checked, as well as at both panels, but the interconnecting power leads were not checked. The checklist only requires the inspector to check that the connections terminate at both ends.	
Recommendation #3: Improve wiring standards. Revise the internal standards regarding installation of ferrules and terminal blocks to ensure proper application of ferrules in the future. Ensure the standards and work processes specify the correct size and termination method(s) of the wire and terminal block. Ensure electrical standards/procedures for future projects require an integrity test of electrical connections (e.g., tug test, correct size and method of terminations, etc.) after installation and during commissioning.	

5.1.4.2 Risk Assessment of Large-scale Ground Compaction Activities

Site personnel noted that raising the site above the flood plain required elevating the site higher than is typical for other similar company sites. For this reason, more ground compaction work was required. Also, this compaction work was performed later in the construction schedule than typical. It was also noted that on the date of the event, ground compaction was being performed using a heavy equipment vibratory single drum compactor. This resulted in a greater magnitude of ground movement than the typical compaction performed during construction (and in some cases commissioning). In most cases, a smaller vibratory plate compactor is used.

The team determined that, although a risk assessment was conducted along with the elevation analysis for the compressor station, there was no assessment that specifically addressed the risks associated with the magnitude or timing of the large-scale ground compaction activities being conducted at the time the facility was being commissioned. The absence of this risk assessment could have contributed to the event. Identification of the non-routine nature of this activity and the larger magnitude of the vibration may have led to preventative measures that would reduce the likelihood of creating a loose connection.

Table 6 summarizes the Risk Assessment barrier as the barrier pertains to the large-scale ground compaction activities done as part of construction.

Table 6: Analysis of Barrier: Risk Assessment of Large-scale Ground Compaction Activities

Barrier: Risk Assessment of Large-scale Ground Compaction Activities	**Status for Event:** Missing
Immediate Cause: IC18. *Failure to Identify Hazard* A ground compacting activity, which is not in the commissioning manual/checklist, was being performed as part of the construction activities. This activity created vibrations that may have caused a temporary open circuit.	
Basic Cause: BC11.2. *Inadequate Identification of Failure Mode* The risk assessment conducted with the elevation analysis did not consider timing of compaction activities with regard to other commissioning activities. The ground compacting that was being performed was non-routine, in that it exceeded the normal magnitude of compaction performed during construction at other similar sites.	
Recommendation #4: For future application, ensure a requirement for risk assessment is in place for non-routine, rarely-conducted activities or those that are different in magnitude than normal to ensure the impacts on facility components and equipment are understood and managed appropriately.	

6 SUMMARY AND CONCLUSIONS

An unplanned event that triggered the ESD system and subsequent blowdown at the Algonquin Gas Transmission, LLC (AGT) Weymouth Compressor Station in Weymouth, Massachusetts, on September 30, 2020. The ESD system is designed to monitor various safety and operating parameters, isolate and depressurize the system, placing the station into a safe state. In this instance, depressurization resulted in a release of approximately 195,000 cubic feet (195 mscf) of natural gas. The release was associated with a loss of 129 V_{DC} power to the ESD Panel caused by an open circuit. The loss of power associated with an open circuit is the direct cause, and two scenarios were evaluated. Factors associated with barriers for both scenarios could have led to the power failure that ultimately preceded the ESD and triggered a controlled natural gas release.

The RCFA of the September 30, 2020 ESD event identified two immediate cause scenarios that may have led to an open circuit that triggered the ESD.

Scenario 1 - *Open circuit caused by faulty equipment, loose connection, or damage during shipping*.

Scenario 2 - *Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction*. Scheduled ground compaction activities were occurring at the compressor station at the time of the event. During interviews and while DNV GL was on site, the vibrations caused by this activity were described as unusually strong.

Analysis of these scenarios identified three (3) primary barriers (one was shared by both scenarios) that could be implemented and/or improved to reduce the likelihood of a similar event from occurring in the future:

- Requirements and conditions for storage of electrical equipment and components.
- The commissioning plan and procedures (including onsite wiring assembly).
- The risk assessment for non-routine activities such as the Large-scale Ground Compaction that was performed during commissioning at the Weymouth Compressor Station.

The lessons learned and corresponding recommendations for improvement pertaining to these three barriers are discussed below.

1. **Clear Specifications and Communication with Vendors**

Currently, the specifications given by AGT to their vendors are focused on the requirements for assembly and testing of components, including requirements for how the components are marked, packaged, stored, and transported. These requirements provide assurance that the necessary actions to be taken prior to and during installation are understood. By communicating any additional requirements for special circumstances, such as unanticipated extended schedules and extended storage, AGT can have further assurance that risks associated with storage during future delays are appropriately managed.

2. **Consideration of Risks associated with Unanticipated Extended Schedules**

Implementation of a working document or internal standard that addresses considerations to be made when projects are delayed or put on hold for long periods of time will help ensure items, such as hazard identification, long-term storage of components, and communication of special circumstances to vendors will be addressed.

3. **Improvements to Wiring Standards**

The existing wiring standards and requirements do require ferrules on terminal blocks; however, installation requirements (i.e., size and manufacturer) of the ferrules are not included within the standard. Revising the standards regarding installation of ferrules and terminal blocks will help ensure proper application of ferrules in the future.

The current practice is for a tug test to be performed by the Electrician when wiring is initially installed; however, only a visual inspection is required as part of pre-startup checks. Revise the electrical standards and/or procedures to require integrity testing of electrical connections (e.g., tug test) after installation and during commissioning to provide assurance that the connections are sound in future projects and applications.

4. **Increased Awareness of non-routine Activities and Require Risk Assessment**

The large-scale ground compaction activity being done as part of construction was not identified as a non-routine activity, because compaction is commonly done; however, in this case, the magnitude and timing of the activity (in terms of vibration) was beyond what is typical. Increasing awareness among staff and requiring risk assessment for non-routine, rarely-conducted activities or those that differ from the norm will help ensure the impacts on facility components and equipment, as well as safety, are understood and managed appropriately.

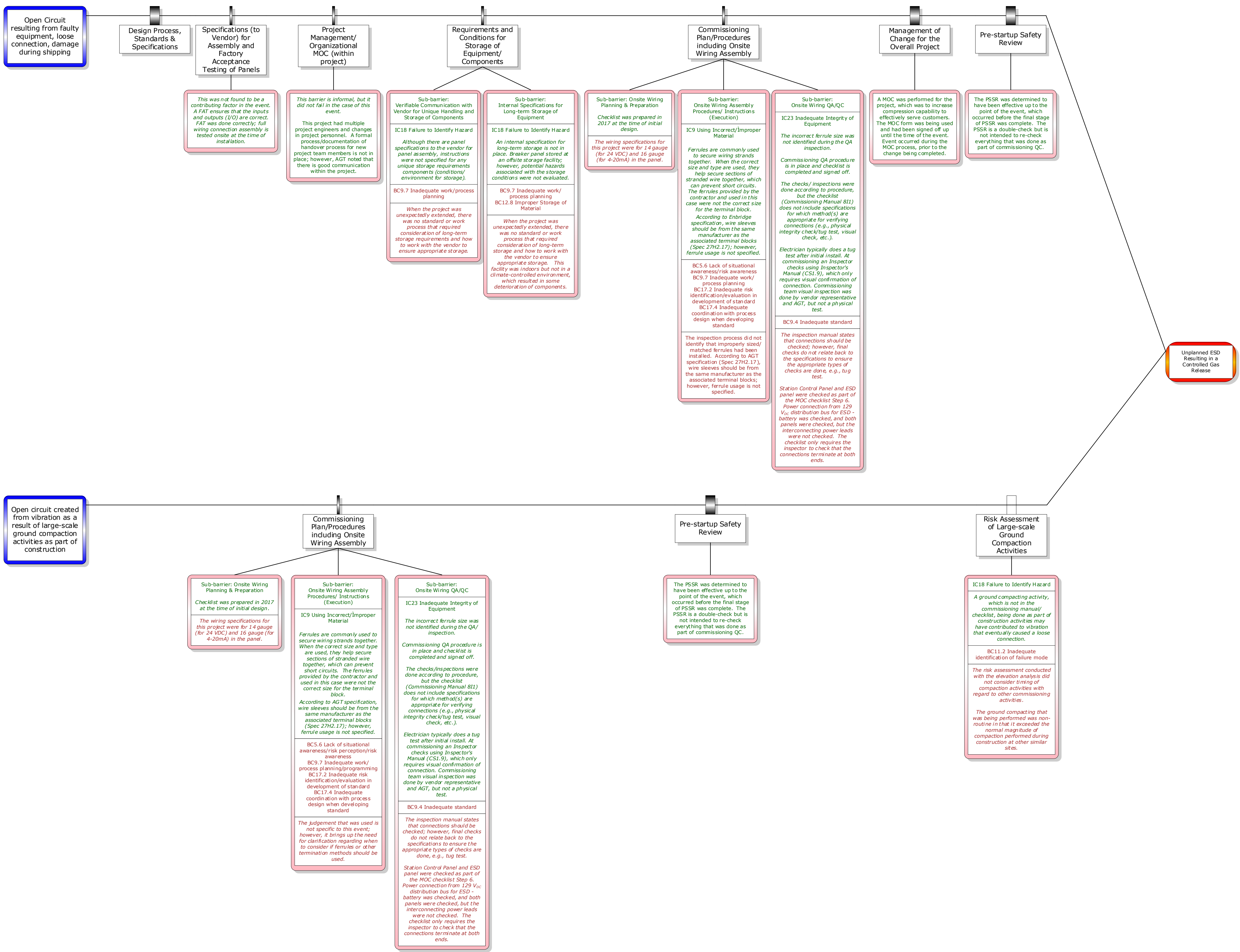
7 REFERENCES

[1] DNV GL USA, Inc., "International Safety Rating System (ISRS) Workbook 8.1".

[2] American Institute of Chemical Engineers (AIChE), "https://www.aiche.org/ccps/resources/glossary/process-safety-glossary/pre-startup-safety-review-pssr".

APPENDIX A

BSCAT Diagram for Weymouth Compressor Station Emergency Shutdown Event


Open Circuit resulting from faulty equipment, loose connection, damage during shipping
Design Process, Standards & Specifications
Specifications (to Vendor) for Assembly and Factory Acceptance Testing of Panels
This was not found to be a contributing factor in the event. A FAT ensures that the inputs and outputs (I/O) are correct. FAT was done correctly; full wiring connection assembly is tested onsite at the time of installation.
Project Management/ Organizational MOC (within project)
This barrier is informal, but it did not fail in the case of this event.
This project had multiple project engineers and changes in project personnel. A formal process/documentation of handover process for new project team members is not in place; however, AGT noted that there is good communication within the project.
Requirements and Conditions for Storage of Equipment/ Components
Sub-barrier: Verifiable Communication with Vendor for Unique Handling and Storage of Components
IC18 Failure to Identify Hazard
Although there are panel specifications to the vendor for panel assembly, instructions were not specified for any unique storage requirements components (conditions/ environment for storage).
BC9.7 Inadequate work/process planning
When the project was unexpectedly extended, there was no standard or work process that required consideration of long-term storage requirements and how to work with the vendor to ensure appropriate storage.
Sub-barrier: Internal Specifications for Long-term Storage of Equipment
IC18 Failure to Identify Hazard
An internal specification for long-term storage is not in place. Breaker panel stored at an offsite storage facility; however, potential hazards associated with the storage conditions were not evaluated.
BC9.7 Inadequate work/ process planning
BC12.8 Improper Storage of Material
When the project was unexpectedly extended, there was no standard or work process that required consideration of long-term storage and how to work with the vendor to ensure appropriate storage. This facility was indoors but not in a climate-controlled environment, which resulted in some deterioration of components.
Commissioning Plan/Procedures including Onsite Wiring Assembly
Sub-barrier: Onsite Wiring Planning & Preparation
Checklist was prepared in 2017 at the time of initial design.
The wiring specifications for this project were for 14 gauge (for 24 VDC) and 16 gauge (for 4-20mA) in the panel.
Sub-barrier: Onsite Wiring Assembly Procedures/ Instructions (Execution)
IC9 Using Incorrect/Ìmproper Material
Ferrules are commonly used to secure wiring strands together. When the correct size and type are used, they help secure sections of stranded wire together, which can prevent short circuits. The ferrules provided by the contractor and used in this case were not the correct size for the terminal block.
According to Enbridge specification, wire sleeves should be from the same manufacturer as the associated terminal blocks (Spec 27H2.17); however, ferrule usage is not specified.
BC5.6 Lack of situational awareness/risk awareness
BC9.7 Inadequate work/ process planning
BC17.2 Inadequate risk identification/evaluation in development of standard
BC17.4 Inadequate coordination with process design when developing standard
The inspection process did not identify that improperly sized/ matched ferrules had been installed. According to AGT specification (Spec 27H2.17), wire sleeves should be from the same manufacturer as the associated terminal blocks; however, ferrule usage is not specified.
Sub-barrier: Onsite Wiring QA/QC
IC23 Inadequate Integrity of Equipment
The incorrect ferrule size was not identified during the QA inspection.
Commissioning QA procedure is in place and checklist is completed and signed off.
The checks/ inspections were done according to procedure, but the checklist (Commissioning Manual 8I1) does not include specifications for which method(s) are appropriate for verifying connections (e.g., physical integrity check/tug test, visual check, etc.).
Electrician typically does a tug test after initial install. At commissioning an Inspector checks using Inspector's Manual (CS1.9), which only requires visual confirmation of connection. Commissioning team visual inspection was done by vendor representative and AGT, but not a physical test.
BC9.4 Inadequate standard
The inspection manual states that connections should be checked; however, final checks do not relate back to the specifications to ensure the appropriate types of checks are done, e.g., tug test.
Station Control Panel and ESD panel were checked as part of the MOC checklist Step 6. Power connection from 129 V_{DC} distribution bus for ESD - battery was checked, and both panels were checked, but the interconnecting power leads were not checked. The checklist only requires the inspector to check that the connections terminate at both ends.
Management of Change for the Overall Project
A MOC was performed for the project, which was to increase compression capability to effectively serve customers. The MOC form was being used and had been signed off up until the time of the event. Event occurred during the MOC process, prior to the change being completed.
Pre-startup Safety Review
The PSSR was determined to have been effective up to the point of the event, which occurred before the final stage of PSSR was complete. The PSSR is a double-check but is not intended to re-check everything that was done as part of commissioning QC.
Unplanned ESD Resulting in a Controlled Gas Release
Open circuit created from vibration as a result of large-scale ground compaction activities as part of construction
Commissioning Plan/Procedures including Onsite Wiring Assembly
Sub-barrier: Onsite Wiring Planning & Preparation
Checklist was prepared in 2017 at the time of initial design.
The wiring specifications for this project were for 14 gauge (for 24 VDC) and 16 gauge (for 4-20mA) in the panel.
Sub-barrier: Onsite Wiring Assembly Procedures/ Instructions (Execution)
IC9 Using Incorrect/Ìmproper Material
Ferrules are commonly used to secure wiring strands together. When the correct size and type are used, they help secure sections of stranded wire together, which can prevent short circuits. The ferrules provided by the contractor and used in this case were not the correct size for the terminal block.
According to AGT specification, wire sleeves should be from the same manufacturer as the associated terminal blocks (Spec 27H2.17); however, ferrule usage is not specified.
BC5.6 Lack of situational awareness/risk perception/risk awareness
BC9.7 Inadequate work/ process planning/programming
BC17.2 Inadequate risk identification/evaluation in development of standard
BC17.4 Inadequate coordination with process design when developing standard
The judgement that was used is not specific to this event; however, it brings up the need for clarification regarding when to consider if ferrules or other termination methods should be used.
Sub-barrier: Onsite Wiring QA/QC
IC23 Inadequate Integrity of Equipment
The incorrect ferrule size was not identified during the QA/ inspection.
Commissioning QA procedure is in place and checklist is completed and signed off.
The checks/inspections were done according to procedure, but the checklist (Commissioning Manual 8I1) does not include specifications for which method(s) are appropriate for verifying connections (e.g., physical integrity check/tug test, visual check, etc.).
Electrician typically does a tug test after initial install. At commissioning an Inspector checks using Inspector's Manual (CS1.9), which only requires visual confirmation of connection. Commissioning team visual inspection was done by vendor representative and AGT, but not a physical test.
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The inspection manual states that connections should be checked; however, final checks do not relate back to the specifications to ensure the appropriate types of checks are done, e.g., tug test.
Station Control Panel and ESD panel were checked as part of the MOC checklist Step 6. Power connection from 129 V_{DC} distribution bus for ESD - battery was checked, and both panels were checked, but the interconnecting power leads were not checked. The checklist only requires the inspector to check that the connections terminate at both ends.
Pre-startup Safety Review
The PSSR was determined to have been effective up to the point of the event, which occurred before the final stage of PSSR was complete. The PSSR is a double-check but is not intended to re-check everything that was done as part of commissioning QC.
Risk Assessment of Large-scale Ground Compaction Activities
IC18 Failure to Identify Hazard
A ground compacting activity, which is not in the commissioning manual/ checklist, being done as part of construction activities may have contributed to vibration that eventually caused a loose connection.
BC11.2 Inadequate identification of failure mode
The risk assessment conducted with the elevation analysis did not consider timing of compaction activities with regard to other commissioning activities.
The ground compacting that was being performed was non-routine in that it exceeded the normal magnitude of compaction performed during construction at other similar sites.

About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.