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# Hazard and Operability Study for the Ammonia Fuel Systems at the National Transportation Research Center


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**June 2023**

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Buildings and Transportation Science Division

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# 1. INTRODUCTION

Oak Ridge National Laboratory's (ORNL's) Buildings and Transportation Science Division (BTSD) plans to operate research engines fueled by ammonia in two engine test cells at the National Transportation Research Center (NTRC). A scientific need has recently emerged to evaluate the suitability of liquid anhydrous ammonia as a low-lifecycle-carbon fuel source for difficult-to-electrify transportation sectors, including the marine sector. Therefore, BTSD plans to install an ammonia storage and delivery system to 2360 HVC engine research labs L125 (Cell 3) and L111 (Cell 7) capable of delivering 35 and 75 lb/h, respectively. These laboratories are specifically designed to allow for engine and fuels research and development, and they have existing safety systems for mitigating risks associated with toxics and flammables. Anhydrous ammonia is toxic and flammable, and the system will use relatively large quantities compared with standard gas bottles. Ammonia is one of the most widely produced chemicals in the world, and the hazards associated with toxicity and flammability are well understood. Ammonia storage for use in engine research at NTRC is anticipated to take the form of an ammonia tank with capacity of 1,000 water gallons; this quantity will remain below the threshold quantity of 10,000 lb (~2,000 gal) used both by the US Environmental Protection Agency for reporting under the Emergency Planning and Community Right to Know Act and for Risk Management Program requirements, and also by the US Occupational Safety and Health Administration for Process Safety Management requirements.[1] ORNL's Environmental Protection Services Division was also consulted to verify that the quantities of ammonia anticipated to be used would be in compliance with environmental regulations. The Environmental Protection Services Division staff confirmed that the anticipated quantities fall below ORNL's permit thresholds. However, because of the hazards associated with anhydrous ammonia, the quantities to be used, and the limited experience with similar quantities of ammonia at ORNL, BTSD decided to perform a hazard and operability (HazOp) study on the ammonia storage and delivery system.

# 2. SCOPE

The scope of this HazOp study includes the conceptual design and operation of the system. The conceptual process and instrumentation drawing (P&ID) for the system was reviewed and used as the basis for this study. The P&ID used for the study is contained in Appendix A. The design reviewed in this HazOp study is preliminary, and the final design will be informed by the results of this study. Because of the preliminary nature of the design, this report is considered a "living document" and may be revised in the future to include additional details. A slide deck describing the system in more detail was developed by the principal investigator and can be made available upon request.

This study is not an assessment and does not seek to identify formal findings, observations, or opportunities for improvements. Instead, it is intended to be an analysis of system performance with regard to hazards and operability that identifies and characterizes risks and the mitigating mechanisms in place. If the team identified risks that were not mitigated to an acceptable level, a recommendation was generated.

In general, a HazOp study does not attempt to engineer risk mitigation solutions and typically presents a recommendation to either investigate further or develop an engineering or administrative approach to further mitigate the risk. However, additional mitigating measures or safeguards often become evident during the course of the study. In these cases, the recommendations are more specific.

[1] US Environmental Protection Agency. 2015. *Accident Prevention and Response Manual for Anhydrous Ammonia Refrigeration System Operators*.

# 3. HAZOP APPROACH

In general, a HazOp study investigates the tolerance of a system to deviations. The system is divided into discrete "nodes," and each node is examined for behavior when subjected to deviations to its normal operating parameters or process variables, such as temperature, flow, and pressure. Nodes are selected such that they include components that share similar normal operating parameters. The P&ID with nodes identified is included in Appendix A. For each node, a set of "guide words" (Table 1) is used to describe deviations and guide the discussion toward analyzing the effects of the deviations on the system. The analysis determines the potential causes of the deviation, as well as the potential unmitigated consequences. The risks for the stated consequences are evaluated (Section 4), and the existing safeguards are cited. If the analysis resulted in recommendations, they are stated, as well.

**Table 1. HazOp guide words**

| Guide word | Meaning | Examples |
|---|---|---|
| NO, NOT, or NONE | The complete negation of | No flow. No stirring. Procedure not used. |
| LESS, LOW, or SHORT | A quantitative decrease | Low temperature. Low flow. Low concentration. Low pressure. Vacuum. Low level. Empty. Too little time. Sooner. |
| MORE, HIGH, or LONG | A quantitative increase | High temperature. High flow. High concentration. High pressure. High level. Full or overfilled. Too much time. Later. |
| PART OF | Only some of the design and/or operating intentions achieved | Recipe component omitted. Procedure step omitted. |
| AS WELL AS or ALSO | All of the design and/or operating intentions achieved, along with additional constituents not part of the design and/or operating intentions | Contamination of process streams. Contamination in source materials. Incomplete purge. Additional step performed that is not in procedure. |
| OTHER THAN | A substitution not part of the design and/or operating intentions or a deviation from normal operations | Wrong reagent used. Something else flows. Unintended reaction. Incorrect operating parameter read by operator. Unanticipated phase change. Maintenance. |
| REVERSE | The logical opposite of the design and/or operating intentions | Reverse flow. Reverse rotation. Procedure executed out of order. |
| WHERE ELSE | A location other than the design and/or operating intentions | Flow in incorrect line. External leak. Spill. |

Where applicable, the following process variables were evaluated for each node: flow, pressure, temperature, and reaction. Additionally, utilities including electric power, plant air, plant process water, laboratory ventilation, and the argon supply trailer were analyzed. A HazOp deviation guide was developed for this study and is included in Appendix B.

# 4. RISK ANALYSIS APPROACH

A key element of a HazOp study is to characterize the risk associated with each deviation consequence. Each consequence is assigned a likelihood and severity rating such that the overall unmitigated risk can be determined from a risk matrix. This allows for a qualitative comparison or risk magnitude for each consequence and provides a means to determine a threshold for consideration of additional safeguards or actions. For this HazOp, we considered two types of risk—actual and administrative. Actual risks can result in tangible loss, such as loss of life, severe injury, property damage, or environmental damage. Administrative risks are related to more intangible effects such as project delays or shutdown, damage to ORNL's reputation, and so on. To provide a quantitative basis for comparison of risks, each postulated process deviation is assigned a likelihood based on Table 2, as well as a severity based on Table 3.

**Table 2. Risk likelihood determination**

| Likelihood | Description | Examples |
|---|---|---|
| Frequent (F) | An event that is known to occur regularly. Likely to happen one to several times each year. | Minor leaks or spills. Internally leaking valves. Indicators or gauges reading incorrectly or losing calibration. Minor equipment failure for non–preventively maintained equipment. Minor operator error. Procedure not being followed completely or shortcut being taken. |
| Occasional (O) | An event that does not occur regularly but is not unexpected. Likely to happen approximately every 1 to 10 years. | Instrument failure. Failure of preventively maintained equipment. Belt failure. Externally leaking valves and fittings. Short power/utility outages. |
| Unlikely (U) | An event that is not expected to occur in a specific facility but is an occasional event in the industry. Likely to happen every 10 years or more. | Major equipment breakdown. Extended power/utility outages. Significant operator error or intentional misconduct. Minor fire. |
| Rare (R) | An event that is not expected to occur in the specific facility and occurs only rarely in the industry. Considered highly unlikely but not impossible. | Pressure vessel failure. Line rupture without external influence. Major fire. Sabotage. |

**Table 3. Risk severity determination**

| Severity | Actual | Administrative |
|---|---|---|
| High (H) | Can cause death, very serious injury, injury to the public, substantial property damage, grave damage to the environment. | May result in permanent or long-term shutdown of the project, substantial damage to ORNL's reputation. |
| Medium (M) | Can cause serious injury, significant releases to the environment, serious occupational illness, significant property damage, exposures in exceedance of regulatory limits. | May result in significant project delays, significant project expenditures, lengthy investigations, damage to ORNL's reputation. |
| Low (L) | Can cause minor injury, exposures above action levels but below regulatory limits, minor impact to the environment, minor property damage, little to no off-site impact. | May result in project delays, investigations, internal and external reporting, corrective actions. |
| Very low (V) | Not likely to result in injury, illness, exposure, or impact to the environment. | May result in internal reporting, possible corrective actions. May be considered a "near miss." |

The “actual” and “administrative” severity categories are considered separately, and the highest severity rating of the two categories is selected for the risk determination. Once the likelihood and severity have been selected for a deviation, they are cross-referenced to a risk matrix (Table 4) to determine an overall risk.

- Risks in the orange or red category are generally considered unacceptable. When an unacceptable risk was encountered, the team carefully considered the safeguards in place to mitigate the risk to determine if they were appropriate. If the team determined that additional safeguards were necessary, then they made a recommendation.
- Risks in the yellow category are generally considered acceptable, although consideration should be given to additional safeguards to further mitigate the risk. For these cases, the team also evaluated the existing safeguards to determine if there were additional opportunities to reduce the risk and made recommendations as appropriate.
- Risks in the light green or dark green category are generally considered “desirable”, and no additional measures are typically necessary. However, the team still evaluated these risks, particularly from an administrative standpoint.

Although the HazOp process is a comprehensive approach to hazard analysis, every possible deviation or risk cannot be anticipated. Consequently, this analysis does not eliminate risk. If the recommendations identified in this analysis are implemented, risks will be reduced but not eliminated. Therefore, those who operate this system must remain aware that risks still exist and should exercise due caution.

**Table 4. Risk matrix**

| | | | | | |
|---|---|---|---|---|---|
| **Severity** | **High (H)** | High (H)<br>Rare (R) | High (H)<br>Unlikely (U) | High (H)<br>Occasional (O) | High (H)<br>Frequent (F) |
| | **Medium (M)** | Medium (M)<br>Rare (R) | Medium (M)<br>Unlikely (U) | Medium (M)<br>Occasional (O) | Medium (M)<br>Frequent (F) |
| | **Low (L)** | Low (L)<br>Rare (R) | Low (L)<br>Unlikely (U) | Low (L)<br>Occasional (O) | Low (L)<br>Frequent (F) |
| | **Very low (V)** | Very low (V)<br>Rare (R) | Very low (V)<br>Unlikely (U) | Very low (V)<br>Occasional (O) | Very low (V)<br>Frequent (F) |
| | | **Rare (R)** | **Unlikely (U)** | **Occasional (O)** | **Frequent (F)** |
| | | **Likelihood** | | | |

| | |
|---|---|
| Red | Unacceptable |
| Orange | Unacceptable |
| Yellow | Acceptable, but additional safeguards should be considered |
| Light green | Desirable |
| Dark green | Desirable |

## 5. HAZOP TEAM

The HazOp team included the following members:

Facilitator: Tim Gillespie, Senior System Safety Analyst
Team member: Michael Windsor, QHSP

Team member: Jason Case, Research Operations
Team member: Brian Kaul, Principal Investigator and Lab Space Manager
Team member: Scott Curran, Principal Investigator and Group Leader
Team member: Eric Laubach, Fire Protection Engineer
Team member: Mark Lower, Facility Engineer

## 6. RESULTS

The HazOp study examined each node identified in Appendix A and applied the guide words to each applicable process variable (parameter) deviation. Results were tabulated in the worksheets provided in Appendix D. For each deviation, potential causes and possible consequences were identified. These consequences were then risk-ranked, and the ranking was recorded. The risk ranking was based on unmitigated consequences. The team then listed and evaluated existing safeguards to determine if they sufficiently reduced the risk identified. If additional safeguards were deemed necessary, then the team generated a recommendation. Prior to closure of this report, the assigned personnel identified resolutions for each recommended action. A summary of the recommendations is provided in Table 5.

**Table 5. Summary of recommendations**

| Node | Item | Recommendation | Assigned to | Resolution |
|---|---|---|---|---|
| A | A.1.1 | Ensure that the excess flow valve is correctly rated for the flows expected. | POC/SME | Work with the tank supplier to ensure that excess flow valves are appropriately sized when specifying/ordering. |
| A | A.1.2 | Consider firewalling the ammonia tank to isolate it from other flammable fuels. | POC/SME | Coordinate with fire protection on isolation requirements and implement any necessary firewalls prior to tank installation. |
| A | A.1.2 | Verify that the pressure relief valve is adequately sized and ASME- and OSHA-compliant. | POC/SME | Work with the tank supplier to document pressure relief valve compliance. |
| A | A.2.3 | Consider establishing an exclusion zone when the tank is being filled. | POC/SME | Coordinate with the facility operations manager and supplier on procedures for tank filling. |
| A | A.2.3 | Consider adding a step to the operating procedure to document the fill level. | POC/SME | Coordinate with the facility operations manager and supplier on procedures for tank filling. |
| A | A.2.4 | Consider adding a step to the operating procedure to check the pressure on the tank prior to filling. | POC/SME | Coordinate with the facility operations manager and supplier on procedures for tank filling. |
| A | A.2.4 | Investigate a method to monitor tank pressure from the control room. | POC/SME | Investigate options for remote monitoring of the tank pressure. |
| A | A.3.3 | Evaluate the need for a scrubber system for ventilation. | POC/SME | Coordinate with the ESH&Q team to determine scrubber requirements and incorporate into final design. |
| A | A.3.3 | Consider adding a manual isolation valve. | POC/SME | Include manual isolation valves, which were not shown in the conceptual P&ID for clarity. |
| A | A.3.5 | Consider putting an annunciator in the control room to alert operators to ammonia being detected. | POC/SME | Set ammonia detectors to trigger an alert in the control room. |

**Table 5. Summary of recommendations (continued)**

| Node | Item | Recommendation | Assigned to | Resolution |
|---|---|---|---|---|
| A | A.3.5 | Develop a process to ensure that ammonia detectors are calibrated and tested routinely. | POC/SME | Coordinate with the facility operations manager/principal investigators to include ammonia detectors in the calibration schedule along with existing lower explosive limit and other gas detectors. |
| A | A.3.5 | Consider the use of redundant ammonia sensors. | POC/SME | Coordinate with the ESH&Q team to determine any locations where redundant sensors may be desirable. |
| B | B.2.3 | When selecting the pump, consider a pump that produces maximum pressure only slightly higher than needed and that will not be damaged by deadheading. | POC/SME | Work with the tank supplier to ensure appropriate pump specifications. |
| C | All | Determine the appropriate ammonia scrubber system and install in ventilation system. | POC/SME | Specify and install an appropriate scrubber for the purge system if needed based on atmospheric release modeling. |
| C | All | Develop a process to monitor ventilation flow to determine adequate flow prior to purge. | POC/SME | If the purge vent is connected to a forced-air ventilation system, interlock it appropriately (may not be applicable with dedicated scrubber, in which case scrubber inspection prior to purge will be conducted). |
| D | D.1.2 | Consider installing ammonia detectors in the cells. | POC/SME | Install ammonia detectors in test cells and control rooms. |
| D | D.2.3 | Consider installing ammonia pressure monitoring for the injection system. | POC/SME | Install pressure, temperature, and flow instrumentation as appropriate. |
| D | D.3.3 | Consider plumbing the rupture disc in Cell 7 to the engine exhaust stack. | POC/SME | Plumb the exhaust rupture to the engine exhaust stack to ensure proper ventilation in case of failure. |
| D | D.3.3 | Evaluate a process to prevent opening ammonia valve unless the engine is spinning. | POC/SME | Implement interlocks for the ammonia valve to ensure safe operation. |
| D | D.3.6 | Consider interlocking ammonia shutoff to ammonia flow. | POC/SME | Implement interlocks for the ammonia valve to ensure safe operation. |
| D | All | Consider crankcase purge capability for Cell 3. | POC/SME | Evaluate Cell 3 ISB engine crankcase ventilation and adapt as needed to ensure effective crankcase purge. |
| D | All | Consider redirecting crankcase vent to cell exhaust. | POC/SME | Direct air from the Cell 7 dry sump oil/air separator to exhaust ventilation. |
| D | All | Consider monitoring pressure differential between cells and the control room to ensure that the control room remains positive. | POC/SME | Install appropriate monitoring on cell ventilation systems to ensure negative pressure in engine test cells. |
| E | E.2.1 | Consider installing a double block and bleed at the Dewar to prevent ammonia backflow into Dewar. | POC/SME | Include a double block and bleed system on the purge gas system to prevent backflow to nitrogen supply Dewar. |

**Table 5. Summary of recommendations (continued)**

| Node | Item | Recommendation | Assigned to | Resolution |
|---|---|---|---|---|
| E | E.2.1 | Consider installing an ammonia detector on purge exhaust to verify that purge is complete. | POC/SME | Design the purge gas system with appropriate sensors to verify that purge is complete prior to opening lines. |
| E | E.2.1 | Consider adding a step to the operating procedure to regularly check purge gas supply. | POC/SME | Check the purge gas supply prior to purging. |
| F | F.1.1 | Ensure that all lines are leak tested prior to initial use. | POC/SME | Leak test all lines prior to use. |
| F | F.1.1 | Ensure that all line unions are welded. | POC/SME | Weld all line unions. |
| G | G.1.1 | Determine how the ammonia washdown sprinkler system responds to a power outage. | POC/SME | Consult the vendor to determine how the ammonia washdown sprinkler system responds to a power outage. |
| G | All | Evaluate the need for pressure relief where liquid ammonia could be trapped by closed valves during an outage | POC/SME | Work with a pressure SME to evaluate the need for pressure relief on lines where liquid ammonia may be trapped. |

Notably, these recommendations may not represent the best solution, and the team may opt to use a different approach.

## 7. ADDITIONAL RECOMMENDATIONS

Management of change is a critical aspect of system safety. Because this is an experimental process, it is possible that the system will be reconfigured as the experiment proceeds. Modifications to the system may have unanticipated consequences and therefore, any modifications that change the intent of the system should be reviewed in a manner similar to that used in this study with a level of rigor commensurate with the complexity of the modification.

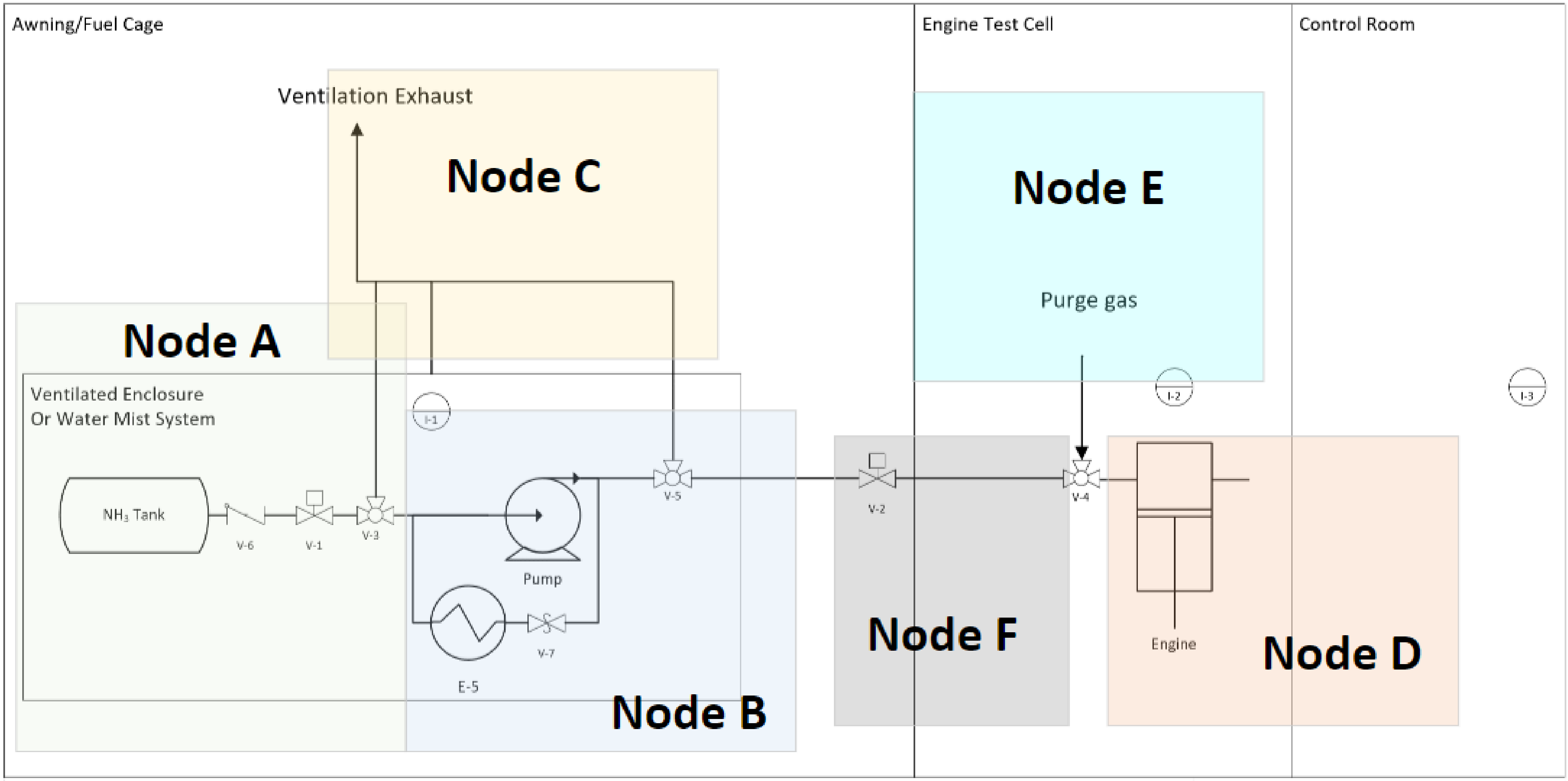
## 8. PROCESS NODES FOR HAZOP

A diagram of the preliminary bulk ammonia storage and fueling system design considered for this analysis is shown in Appendix A and consists of the following:

- Node A: Ammonia storage vessel and additional safety system
- Node B: Ammonia fuel pump
- Node C: Ventilation exhaust for pressure relief (and potential ammonia scrubber)
- Node D: Ammonia fueled engine system
- Node E: Purge gas system
- Node F: Ammonia fuel line from Node A to Node D
- Node G: Utilities (not shown on P&ID)

The final design of the system is subject to refinement based on this HazOp and additional input from the vendor and ORNL's ESH&Q team.

# APPENDIX A. PROCESS NODES



# APPENDIX B. HAZOP DEVIATION GUIDE TABLE

**Table B-1. HazOp deviation guide**

| Guide words / Process variables | No, not, none | Less, low, short | More, high, long | Part of | As well as, also | Other than | Reverse | Where else |
|---|---|---|---|---|---|---|---|---|
| **Flow** | No flow | Low rate, low total | High rate, high total | Missing ingredient | Misdirected flow, impurities, slugs | Wrong material, incorrect indication | Backflow | External leak, spill |
| **Pressure** | Open to atmosphere | Low pressure | High pressure | — | — | — | Vacuum | — |
| **Temperature** | Freezing | Low temperature | High temperature | — | — | — | Auto-refrigeration | Heating or cooling of other components |
| **Level** | Empty | Low level | High level | Low interface | High interface | — | — | Overflow |
| **Agitation** | No mixing | Poor mixing | Excessive mixing | Mixing interrupted | Foaming, extra phase | — | — | Phase separation |
| **Reaction** | No reaction | Slow reaction | Runaway reaction | Partial reaction | Side reaction | Wrong reaction | Decomposition | — |
| **Time** | — | Too short, too little | Too long, too much | — | — | — | — | — |
| **Procedure** | No procedure, procedure not used | Missing steps | Too complex | Step skipped | Extra action, shortcut | Wrong action, maintenance | Out of order | Wrong procedure |
| **Speed** | Stopped | Too slow | Too fast | Out of synch | — | Belt break | Backward, reverse rotation | — |
| **Utilities** | No utilities | Utility voltage, pressure, temperature too low | Utility voltage, pressure, temperature too high | — | Impurities, line noise | Wrong gas, wrong voltage | Backflow | — |
| **Observation** | Reading not taken | Reading error low | Reading error high | Incomplete reading taken | — | Wrong reading taken | — | — |

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# APPENDIX C. HAZOP WORKSHEETS

| | |
|---|---|
| Node: A | Node description: Ammonia tank |
| Drawing(s): Appendix A | Session date: 09/14/2022 |
| Node intended operating parameters:<br>Nominal temperature: Ambient outdoor<br>Nominal pressure: ~115 psig<br>Nominal flow: Variable from ~35 to ~75 lb/h<br>Other: | |
| Component no: | Description: Ammonia tank with capacity from 300 to 2,000 lb |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| A.1.1 | Temp | Low | Cold outdoor temperatures.<br>Liquid nitrogen released from nearby Dewar. | Ammonia freezes in lines, potentially causing damage and leaks. | R | M | GRN | Tank will be equipped with an excess flow valve that will shut off flow when a specific flow rate is exceeded.<br><br>Ammonia detectors will be installed near the tank. | Ensure that excess flow valve is correctly rated for the flows expected. | POC/SME |
| A.1.2 | Temp | High | Hot outdoor temperatures. Fire in nearby stored flammable fuels. Pump overheats. Heat exchanger fails. | Tank overheats and overpressures. Potential explosion due to either combustion or boiling liquid expanding vapor explosion (BLEVE). | U | H | OR | Tank will be equipped with a pressure relief valve. A fire suppression system and ammonia washdown sprinkler system will be installed. | Consider firewalling the ammonia tank to isolate it from other flammable fuels.<br><br>Verify that the pressure relief valve is adequately sized and ASME and OSHA compliant. | POC/SME |
| A.2.1 | Pressure | No | Empty ammonia tank. Incorrect valving. | Experimental impact only. | | | | | | |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| A.2.2 | Pressure | Low | Ammonia tank almost empty. | See A.2.1. | | | | | | |
| A.2.3 | Pressure | High | High temperature. See A.1.2. Overfilled tank not leaving sufficient headspace. | Tank overpressures. Pressure relief valve release. | U | M | YEL | The ammonia vendor will have a filling procedure. There are two ammonia level indicators on the tank. An ammonia washdown sprinkler system will be installed. | Consider establishing an exclusion zone when tank is being filled.<br><br>Consider adding a step to the operating procedure to document the fill level. | POC/SME |
| A.2.4 | Pressure | Reverse | Pump could pull vacuum on the tank. | Possible tank damage. Minimal potential for release due to the limited vacuum pumping capability of the pump. | U | V | GRN | | Consider adding a step to the operating procedure to check the pressure on tank prior to filling.<br><br>Investigate a method to monitor tank pressure from the control room. | POC/SME |
| A.3.1 | Flow | No | See A.2.1. | See A.2.1. | | | | | | |
| A.3.2 | Flow | Low | See A.2.2. | See A.2.2. | | | | | | |
| A.3.3 | Flow | High | Downstream leak. Ventilation valve open. | Potential ammonia leak to ventilation system. | O | L | YEL | The three-way valve will only allow purge gases to vent to the ventilation system. | Evaluate the need for a scrubber system for ventilation.<br><br>Consider adding a manual isolation valve. | POC/SME |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| A.3.4 | Flow | Reverse | Incorrect valving. | No consequences of concern. | | | | Excess flow valve will limit reverse flow. | | |
| A.3.5 | Flow | Where else | Leaks from valves or fittings. | Ammonia release. | O | H | RED | See A.1.1. | Consider putting an annunciator in the control room to alert operators to ammonia being detected.<br><br>Develop a process to ensure that ammonia detectors are calibrated and tested routinely.<br><br>Consider the use of redundant sensors. | POC/SME<br><br>POC/SME<br><br>POC/SME |
| Comments: | | | | | | | | | | |

| Node: B | Node description: Ammonia pump |
|---|---|
| Drawing(s): Appendix A | Session date: 9/14/2022 |
| Node intended operating parameters:<br>Nominal temperature: Ambient to slightly warmer<br>Nominal pressure: ~150 psig<br>Nominal flow: Up to ~110 lb/h<br>Other: | |
| Component no: | Description: The ammonia pump will supply liquid ammonia to the engine test cells at appropriate pressure and flow rates. |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| B.1.1 | Temp | Low | Cold outdoor temperatures. Heat exchanger chiller too cold. | No consequences of concern. | | | | | | |
| B.1.2 | Temp | High | Pump runs hot. | Potential vapor lock resulting in no or low flow. Experimental impact only. | | | | | | |
| B.2.1 | Pressure | No | See A.2.1. | See A.2.2. | | | | | | |
| B.2.2 | Pressure | Low | See A.2.2. | See A.2.2. | | | | | | |
| B.2.3 | Pressure | High | Backpressure regulator valve fails. | Full pump pressure to system. Pump deadheaded and potential damage. Experimental impact only. | | | | All lines and fittings will be pressure rated to much higher pressures than the pump can produce. | When selecting the pump, consider a pump that produces maximum pressure only slightly higher than needed and that will not be damaged by deadheading. | POC/SME |
| B.2.4 | Pressure | Reverse | Incorrect valving. | Experimental impact only | | | | | | |
| B.3.1 | Flow | No | Incorrect valving. Pump failure. | Experimental impact only. | | | | | | |
| B.3.2 | Flow | Low | See B.3.1. | See B.3.1. | | | | | | |
| B.3.3 | Flow | High | Leak in downstream nodes. See Nodes D and E. | | | | | | | |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| B.3.4 | Flow | Reverse | See A.3.4. | See A.3.4. | | | | | | |
| B.3.5 | Flow | Where else | Leak. | See A.3.5. | | | | | | |
| Comments: | | | | | | | | | | |

| Node: C | Node Description: Ventilation system. **NOTE:** This system was not analyzed in depth because a determination of which ventilation system to use has not yet been made. See comments below. |
|---|---|
| Drawing(s): | Session date: |
| | |
| Component no: | Description: Provide ventilation for the purge system. |

| |
|---|
| Comments: During the discussion, it was determined that the ventilation system will need to be scrubbed for ammonia gas. It was also determined that ventilation flow should be monitored and verified prior to purge. See Table 5 for responsibility assignments. |

| Node: D | Node description: Engine ammonia injection system. |
|---|---|
| Drawing(s): Appendix A | Session date: 9/14/2022 |

Node intended operating parameters:
Nominal temperature: Ambient to 100°F
Nominal pressure: ~150 psig
Nominal flow: Variable from ~35 to ~75 lb/h
Other:

| Component no: | Description: Liquid ammonia will be injected into the intake manifold ports of the test engines. |
|---|---|

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| D.1.1 | Temp | Low | No credible cause. | | | | | | | |
| D.1.2 | Temp | High | Fire. | Potential for small ammonia leak. | U | VL | GRN | The engine test cells have emergency cut-off systems, ventilation, fire alarms, and sprinkler systems. | Consider installing ammonia detectors in the cells. | Brian Kaul |
| D.2.1 | Pressure | No | See B.2.1. | See B.2.1. | | | | | | |
| D.2.2 | Pressure | Low | See B.2.2. | See B.2.2. | | | | | | |
| D.2.3 | Pressure | High | High pressure from upstream nodes. | Possible injector seal failure resulting in small leak. | R | M | LT GRN | | Consider installing pressure monitoring for the injection system. | Brian Kaul |
| D.2.4 | Pressure | Reverse | No credible cause. | | | | | | | |
| D.3.1 | Flow | No | See no flow for Nodes A and B. | | | | | | | |
| D.3.2 | Flow | Low | See no flow for Nodes A and B. | | | | | | | |
| D.3.3 | Flow | High | Fuel injector stuck open. | Possible excess ammonia flow into engine and exhaust. Experimental impact only. | | | | | Consider plumbing the rupture disc in Cell 7 to the engine exhaust stack.<br><br>Evaluate a process to prevent opening ammonia valve unless engine is spinning. | Brian Kaul<br><br>Brian Kaul |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| D.3.4 | Flow | Reverse | No credible cause. | | | | | | | |
| D.3.6 | Flow | Where else | Leaks. | Potential ammonia release into cell. | O | H | RED | See D.1.2. | Consider interlocking ammonia shutoff to ammonia flow. | Brian Kaul |
| Comments: Consider crankcase purge capability for Cell 3.<br>Consider redirecting crankcase vent to cell exhaust.<br>Consider monitoring pressure differential between cells and control room to ensure that control room remains positive.<br>See Table 5 for responsibility assignments. | | | | | | | | | | |

| Node: E | Node description: Purge gas system. |
|---|---|
| Drawing(s): Appendix A | Session date: 9/14/2022 |
| Node Intended Operating Parameters:<br>Nominal Temperature: Ambient<br>Nominal Pressure: ~2 bar<br>Nominal Flow: ~2 lpm<br>Other: | |
| Component No: | Description: Purge gas will be supplied by a liquid nitrogen Dewar. Purge will be used to clear lines of ammonia prior to system breach or maintenance. |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| E.1.1 | Temp | Low | No credible cause. | | | | | | | |
| E.1.2 | Temp | High | No credible cause. | | | | | | | |
| E.2.1 | Pressure | No | Empty Dewar. Regulator failure. Incorrect valving. | No purge. Backflow into purge system. Potential exposure on system breach. | O | H | RED | Personnel will wear PPE and respirator during system breach until system is verified to be clear of ammonia. | Consider installing a double block and bleed system at the Dewar to prevent ammonia backflow into Dewar.<br><br>Consider installing an ammonia detector on purge exhaust to verify that purge is complete.<br><br>Consider adding a step to the operating procedure to regularly check purge gas supply. | Brian Kaul<br><br>Brian Kaul<br><br>Brian Kaul |
| E.2.2 | Pressure | Low | Dewar regulator failure. | Slow or no purge. See E.2.1. | | | | | | |
| E.2.3 | Pressure | High | Dewar regulator failure. | Experimental impact only. | | | | Dewar is equipped with a pressure relief valve. | | |
| E.2.4 | Pressure | Reverse | See E.2.1. | See E.2.1. | | | | | | |
| E.3.1 | Flow | No | See E.2.1. | See E.2.1. | | | | | | |
| E.3.2 | Flow | Low | See E.2.2. | See E.2.2. | | | | | | |
| E.3.3 | Flow | High | See E.2.3. | See E.2.3. | | | | | | |

| Item | Parameter | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| E.3.4 | Flow | Reverse | See E.2.1. | See E.2.1. | | | | | | |
| E.3.6 | Flow | Where else | Leak. | No consequences of concern. | | | | | | |
| Comments: | | | | | | | | | | |

| Node: F | Node description: Transfer line(s) from pump to test cells |
|---|---|
| Drawing(s): Appendix A | Session date: 9/14/2022 |
| Other: | |
| Component No: | Description: |

| Item | Adverse Effect | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|
| F.1.1 | Ammonia gas release | Leak or damage to line. | Possible exposure. | R | H | YEL | | Ensure that all lines are leak tested prior to initial use.<br><br>Ensure that all line unions are welded. | Brian Kaul<br><br>Brian Kaul |
| Comments: This node was evaluated using a "What-if" approach. | | | | | | | | | |

| Node: G | Node description: Utilities: electricity, process water, chiller, compressed air |
|---|---|
| Drawing(s): | Session date: |
| Other: | |
| Component No: | Description: |

| Item | Utility | Deviation | Causes | Consequences | L | S | Risk | Safeguards | Recommendations | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| G.1.1 | Electricity | Outage | Various. | No consequences of concern. | | | | All valves are normally closed and will close when power is out. | Determine how the ammonia washdown sprinkler system responds to a power outage. | Brian Kaul |
| G.1.2 | Process water | Outage | Various. | No consequences of concern. | | | | | | |
| G.1.3 | Chiller | Outage | Chiller failure. See B.1.2. | | | | | | | |
| G.1.4 | Compressed air | Outage | Compressor failure. | No consequences of concern. | | | | See F.1.1. | | |
| Comments: Evaluate the need for pressure relief where liquid ammonia could be trapped by closed valves during an outage. See Table 5 for responsibility assignments. | | | | | | | | | | |