ANNEX C

SAFETY FUNCTION REQUIREMENTS

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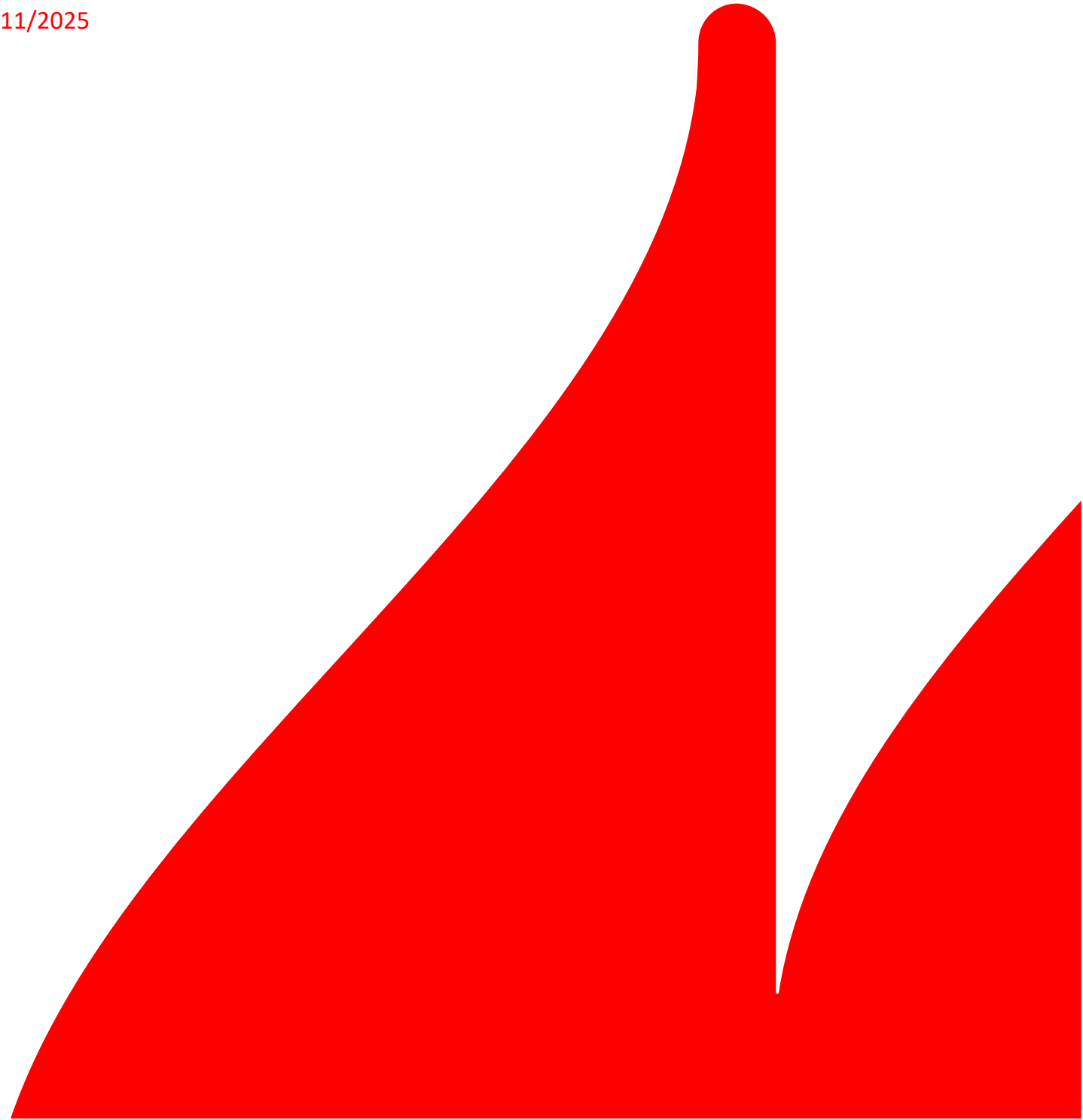

LIST OF TABLES

Table 1: Methanol safety function requirements

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
Bunker station + Transfer to storage tank	Low flashpoint ignition: spray/mist ignition at manifold →Methanol ignites (at ~11–12°C) & wide flammability (~6–36 % vol in air); leaks during transfer pose fire/explosion risks.	• Use of drip-free couplings and hoses • Gas detection (fixed + portable at manifold & low points) • Dedicated ventilation for enclosed/semi-enclosed bunker stations • Ex-rated manifold area • Static grounding and bonding • UV/IR flame detection for invisible flames • Emergency Shutdown (ESD) with quick isolation → Action tier ≈ 40–60 % LFL) driving pump stop + ESD valves (surge-profiled) • Hot-surface survey & shielding of ignition sources • Monitors/lines for pool/spray fires – CCTV • Alcohol-resistant firefighting systems (foam, water spray) • Structured permit-to-transfer with ignition source checklist • A-60 insulation / cofferdam protection between hazardous areas and compartments • Personnel firefighting training and PPE
	Loss of containment at bunkering interface (spray/pool, ignition, exposure) due to hose/coupling failure, mis-connection.	• Dry break + breakaway couplings; keyed connectors • Positive identification (P&ID/label/CCTV) with “check-before-flow” interlock • Manifold drip trays/coamings; • Blank-flange on unused un-used manifold nozzles or sample/drain points • Line-up sensors to confirm the intended flow path is correct and tight • Flow-balance or pressure-decay line-integrity test before ramp-up. • Emergency Shutdown (ESD) with quick isolation → Action tier ≈ 40–60 % LFL) driving pump stop + ESD valves (surge-profiled)
	Toxic vapor exposure: Methanol vapors are harmful when inhaled.	• LEL + Toxic Gas Detectors (fixed and portable) • Dedicated Ventilation • Rapid isolation/ESD • PPE & Emergency Washing Facilities for skin/eye wash • Security Zone - controlled, restricted area • Procedural Controls i.e, pre-bunkering checks and training
	Invisible flame hazard: Flames are easily missed,	• UV/IR or Multi-spectrum Flame Detectors

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
	especially in daylight.	• Redundant Detection (UV + IR) • Portable thermal imaging for fire patrols and response teams • Rapid Fire Alarm & Suppression Activation • Automatic actions; ESD interlock • Staff Training for Invisible Flames • CCTV or Thermal Imaging Supplements
	Static discharge ignition risk: Fuel flow may generate static electricity.	• Limit flow velocity (≤ 3 m/s) through transfer piping. • Bonding and grounding hoses, couplings, and equipment to dissipate charge. • Minimise splash/free-fall at tank inlets • Use conductive materials for all fluid-exposed parts • Implement inert (bottom-up) fill methods to reduce splash and charge accumulation. • Dry-disconnect couplings • Purging/inerting procedures • Operational training
	Inerting/purging failure	• Continous inerting at all times • Arrange bunkering lines for inerting and gas-freeing (pre-purge / post-purge), and drain lines/hoses on completion • Prevent backflow from tanks to the inert-gas (IG) system • Control gas-freeing discharges (high-velocity or protected outlets) • Assure IG availability and quality • Bunkering ESD and remote isolation • Monitoring and trips during bunkering • Vent system & tank strength to withstand purging/inerting (incl. deviations)
	Spills and environmental contamination: Methanol is water-soluble, risking marine pollution.	• Spill containment coamings and trays with closed drainage to a dedicated holding tank, which is inerted and alarmed. • Overfill protection • Dedicated drainage System • Pollution recovery • Spill response - Absorbent spill kits

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Methanol-compatible materials and coatings to minimize corrosion. • Operational procedures for spill response
	Overfill/surge; PRV lift → hazardous vent	• Independent High/High-High level with transfer stop; • Surge-profiled valve closures (anti-hammer); • Routine vents/purges to processing (scrubber/thermal oxidizer/shore system); • Emergency mast only with no-re-ingestion siting. • Grounding/continuity checks on hose/arm.
Storage Tank + Tank Connection Space (TCS) + Transfer Pipes to FPR	Vapor accumulation in TCS → explosion risk	• Ventilation systems to purge flammable vapors from enclosed spaces • Vapor detection (LEL sensors) in TCS and adjacent piping zones • Explosion-Proof Equipment (Ex-Zone Rated) • Automatic Shutdown System • Double containment via cofferdams around tank connections • Controlled tank venting (PRVs, flame arrestors, vertical outlets) • Ignition Source Control • Safe access for inspection and maintenance
	Toxic exposure risks to personnel from inhalation of methanol vapors.	• LEL + Toxic Gas Detection within TCS and piping access areas. • Ventilation / Dilution Systems to prevent vapor build-up in enclosed zones. • Atmospheric Monitoring Alarms integrated into ESD systems. • Personnel Training on hazard recognition and response. • Engineering Controls such as cofferdams around tank connections to reduce leak potential and vapor spread. • Hazard zoning and signage • Personnel Protective Equipment (PPEs)
	Overpressure or vacuum scenarios, especially during temperature fluctuations or vent failure.	• Redundant Pressure/Vacuum Relief Valves (P/V) • Vent system sizing to handle peak bunkering flows • Flame arrestors on vent exits • Vertical vent routing to avoid personnel exposure • Continuous pressure monitoring with alarms • Double-block and bleed valve arrangement on inerting lines

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Gas-tight cofferdams around TCS
	Material degradation/corrosion from prolonged methanol exposure.	• Material Compatibility Selection: Use metals, elastomers, and seals certified for methanol service. • Protective Coatings or Linings to resist chemical attack. • Regular Inspection & Maintenance based on corrosion risk. • Leak Detection & Alarm Systems to catch early failure. • Industry Standard Guidance for Material Selection integrated in design documents.
	Vapor migration from TCS into adjoining compartments.	• Cofferdam with vapor-tight boundaries to physically separate TCS from other spaces. • Ventilation and pressure balancing to prevent migration of flammable vapor. • Gas-tight barriers (e.g., A-60 insulated bulkheads) between TCS and adjacent spaces. • Gas detection in adjacent compartments for early warning of vapor ingress. • Structural layout and access control to isolate TCS and minimize connection pathways.
Fuel Preparation room + Transfer to engine room	Leak-induced methanol vapor and accumulation in enclosed FPR → explosion or toxicity	• Dedicated Ventilation / Air Changes (ACH) (≥30 ACH) • Rapid isolation valves (local/remote), drip trays • Sloped floors and vapor segregation • Tight Compartmentation • Methanol-compatible pumps and seals • Mechanical Interlocks / ESD Activation • Explosion-Proof Electrical Installations • Zoning and Access Control • Training & Response Procedures
	Toxic exposure from elevated vapor levels, especially during maintenance or leak response.	• LEL + Toxic Concentration Alarms: Trigger at low conc. • Mechanical Ventilation (≥ 30 ACH Underpressure) & Purge Systems • Alarm Integration & ESD • Portable Gas Monitors & Procedural Controls: Includes safe work permits, isolation, and pre-maintenance gas clearance protocols. • Personal Protective Equipment (PPE) i.e. respirators, gloves • Training & Drills: Scenario based readiness
	Invisible flame propagation, making detection and response challenging	• UV/IR (or multi-spectrum) Flame Detectors

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Combined Detection Systems: Pair UV/IR with smoke or heat detectors for redundancy. • Rapid Fire Suppression Activation: Flame detection must trigger ESD and fire suppression • systems immediately. • Alcohol-resistant foam coverage • Thermal Imaging Patrol Capability • Training for Crew: Ensure personnel understand invisible flame risks.
	Pump or valve failures, which could initiate uncontained release or system overpressure.	• Pressure Relief Valves (PRVs) or Burst Discs to vent excess pressure • Pump Pressure & Temperature Alarms to detect failures • Emergency Shutdown (ESD) Interlocks triggered by pressure or flow anomalies • Overpressure Protection on Both Supply & Return Loops • Containment—Drip Trays or Secondary Bunding under pumps and valves • Regular Testing & Maintenance of safety components
	Vapor migration through piping into adjacent passages or engine spaces, potentially exceeding safe LEL.	• Gas- and liquid-tight piping through enclosed, non-fuel areas. • Bundled or ducted piping systems to contain leaks. • Ventilation systems to dilute migratory vapor. • LEL sensor installation in adjacent passages and engine room. • Emergency isolation valves in transfer piping routes. • Zone planning and routing layout to minimize vapor ingress pathways.
Engine room	Liquid leaks → fire or toxic pools near hot surfaces	• Methanol flame detection (UV/IR) + gas sensing • Ventilation, drip trays, double piping • Flameproof zones and fire suppression (Class B/liquid) • Rapid ESD valves and combustion monitoring protocols • Comprehensive Heat Insulation & Shielding for all hot surfaces (e.g., turbochargers, exhaust pipes). • Drip Trays or Drainage Systems installed beneath pump and valve assemblies. • Leak Detection Sensors (e.g., LEL detectors) placed near hot surfaces. • Gas-Tight Containment in fuel line assemblies near engines. • Crew Training for maintenance and leak response, especially post-insulation removal.
	Toxic exposure to machinery space personnel and the risk of inhalation	• Fixed LEL + Toxic Gas Detectors: Real-time vapor monitoring.

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Effective Ventilation: Sufficient air changes to dilute methanol vapors. • Alarm-linked Emergency Shutdown (ESD): Automatic fuel isolation upon detection. • Respiratory PPE & Decontamination Stations: Accessible respirators and safety showers. • Safe Entry Procedures: Pre-entry gas checks and clearance protocols. • Crew Training: Regular drills focusing on vapor detection and response.
	Methanol flame invisibility leads to delayed detection	• Dual/Multispectral Flame Detection — UV/IR sensors immediately detecting invisible methanol flames. • Smoke, Heat, or Thermal Imaging Backup — additional detection layers. • Immediate ESD & Shutdown Triggering — upon flame detection. Fixed Alcohol-Resistant Foam (ARAFFF) Systems in engine-room bilge zones. • Portable Thermal Cameras for patrol and response. • Crew Training focusing on recognizing invisible flame indicators (e.g., rapid heat spikes). • Maintenance Checks ensuring detector cleanliness and functionality in engine-room conditions.
	Engine misfires or backfires causing unburned methanol release into the engine room	• Misfire Detection Systems: Utilize combustion pressure sensors, ion-current sensing, or vibration monitoring to detect misfire/backfire events in real-time. • Emergency Shutdown (ESD) Logic: Automatic fuel and ignition cutoff triggered by misfire detection. • Purge Ventilation: High-capacity ventilation or purge fans to quickly evacuate released vapors. • LEL Detection & Alarm: Fixed LEL sensors in engine-room spaces to alert rising vapor levels. • Backflow Prevention: Installation of non-return valves or flame arrestors in fuel lines and exhausts to prevent reverse flow or flashback. • Fire Protection Systems: Readily deployable Local Application Firefighting (LAFF) or bilge foam systems matched to methanol characteristics. • Crew Training & Response Protocols: Drills covering misfire detection, evacuation, and immediate shutdown procedures.
	Fuel return line leaks or service failures	• Pressure Relief Devices: Pressure relief valves (PRVs) or burst discs on the return line to prevent overpressure buildup. • Proper Line Routing: Ensure the return path remains open to fuel tank—not subject to full isolation that could trap pressure. • Leak Detection Alarms: Pressure monitoring and alarms linked to ESD for immediate response. • Containment & Insulation: Drip trays under return line fittings, plus thermal shielding where

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		near hot surfaces. • Crew Training & Procedures: Include safe maintenance protocols addressing return-line handling and response to leaks.

Table 2: Ammonia safety function requirements

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
Bunker station + Transfer to storage tank	Toxic NH_3 release to personnel / atmosphere	• Detection & interlocks; fixed toxic gas detection at bunkering station and detector placement • Ventilation; Mechanical ventilation of enclosed/semi-enclosed bunker stations, loss of ventilation → alarms and trips • Mitigation of released vapour; ammonia vapour processing (scrubber/dissolution/oxidation) or water-mist absorption capability at the bunker station. • Drainage & containment; Drip trays at bunker station with leak detection, remote-closable drain to NH_3 drain tank • Water-spray; Water-spray protecting bunker station with remote operation from bunker control. • PPE & emergency showers; Eyewash/showers and PPE provision • Storage-mode modifiers; Refrigerated/semi-pressurized: cold lines/valves → icing protection, heat tracing, cryo-rated gaskets. Pressurized: design for higher DP, surge control, no vapour-return typical
	Narrow flammability range/ignition risk in presence of sparks or hot surfaces.	• Hazardous & toxic area control • Bonding/earthing & anti-static continuity • Eliminate hot surfaces • Ventilation to prevent build-up • Gas detection at bunker station: fixed NH_3 detectors with alarm/ESD logic; • Water-spray (cooling & vapour knock-down): protect bunker manifold & area with remote-start water spray • ESD & surge-safe valve closure: interlocked bunker ESD valves; • Layout: Require enclosed/semi-enclosed manifold arranged w/o dead spaces, plus ammonia detection, ventilation, vapour processing or water-mist, drip trays & drains • Operational interlocks and pre-bunkering checks - Pre-transfer test: bonding continuity, detectors healthy, ventilation set, ESD link proven, ERS armed, spray system ready, vapour-processing online
	Accumulation of vapours in enclosed/semi-enclosed bunker areas → toxic exposure (and fringe flammability risk)	• Gas Detection and tiered alarms; fixed at low and high points. • Ventilation Requirements; forced mechanical ventilation with defined airflow (e.g. ≥ 6–10 air changes/hour). • Containment & Access Control; airlocks, gas-tight boundaries between bunker area and non-hazardous zones. • Shutdown & Alarm Systems • Redundancy and operational controls; back-up for ventilation and alarms

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Emergency Mitigation Systems; Water spray curtain systems, Automatic venting to safe areas if high concentration detected, Venting discharges meeting safe height and distancing criteria.
	Corrosive vapors and liquid spray, damaging materials	• Material compatibility and segregation; Use compatible materials and insulation • Splash/spray containment • Dedicated NH_3 drain & capture • Coatings & galvanic control • Electrical/inst. robustness • Water spray / deluge coverage (with materials awareness) • Design Robustness & Integrity • Redundancy in containment • Insulation & Cold Temperature • Inspection & replacement rules
	Severe cold burns if liquid ammonia contacts skin or materials	• Human protection & first aid; Deck decontamination shower + eyewash at (or immediately adjacent to) the bunker station; Stage NH_3-compatible PPE at the station. • Spray shields/splash guards on flanges, quick-connects and ERS couplings; solid barriers • Coamed, coated drip trays under all possible leak points; remotely closable drains to a segregated NH_3 drain tank • Detect & isolate before people are exposed; tresholds ppm On alarm: ESD, ventilation divert/boost, route to processingProcedures & drills • Pre-bunkering test pack: shower/eyewash flow & temp check, PPE inspection, detector bump, ventilation mode, ESD/SSL test, drain-tank level; drill
	Vapor cloud formation (dense gas near deck level) with wider dispersion patterns	• Detect early, where the cloud forms; Fixed NH_3 detection at two elevations: low-level, high level • Ventilate for dense gas; For semi-enclosed stations, provide mechanical ventilation • Isolate and depressurize quickly; ESD valves at manifold • Manage the plume path; Vent-mast siting & height, verify no re-ingestion with CFD or tracer-gas tests for critical headings/winds • Effluent/runoff control; Drip trays → closed NH_3 drains → dedicated tank → vapour-processing, with heat tracing • Operational barriers; Pre-bunkering meteorology check (windsock/anemometer); set abort criteria
	Overpressure / surge during transfer; tank overfill; PRV lift → mast release & re-ingestion	• Overpressure & surge control during transfer; Valve stroking & sequencing: set ESD ≤ 5 s unless surge analysis justifies slower; interlock pump stop → ESD valves close; monitor transients at manifold & tank neck. Hydraulic surge mitigations: VSD pump ramp-down, anti-

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		slam checks, controlled closure profiles, relief of liquid-full trapped sections to vapour-processing; Linked ship/shore logic (SSL/ERS) so both sides stop flow on any high-level/pressure trip • Tank overfill prevention; Independent level protection: continuous gauging + High-High (HH) alarm + separate automatic overfill shutoff; Fail-safe action: HH triggers bunker ESD, closes tank filling valves, and stops shore pumps; closure time must prevent overfill. • PRV lift → discharge management; Normal: route conditioning/venting to processing (scrubber/oxidizer/diffusion tank) sized for credible loads; fit outlet monitoring points. Emergency: mast discharge allowed only per BV; mast height ≥ B/3 or 6 m (greater) and distance ≥ B or 25 m from intakes; provide detection at mast/near intakes; prove no re-ingestion by CFD/tracer. • Ventilation & drains that help pressure control; ≥ 30 ACH (semi-enclosed stations) with auto-divert to processing on alarm; heat-traced NH_3 drain system so icing doesn't trap pressure/flow→ Important: Pressure Relief & Venting; Containment & Layout; Design Redundancy & Fail-Safe; Operational Controls
	Hose/coupling failure; mis-connection at manifold	• Make the connection intrinsically safer: Dry-disconnect couplings (DD/CC) at the manifold, with internal shut-off valves. Specify ammonia-compatible sealing (PTFE/metallic) and materials; Emergency Release System (ERS) in the hose string: ERC (or PERC) + interlocked isolating valves; Breakaway coupling to prevent hose rupture and whip if a drift/pull occurs outside the envelope. • Engineer-out mis-connection: Liquid vs vapour connectors with mechanical keying / non-interchangeable interfaces and distinct sizes/orientation; SSL/Linked ESD logic that won't permit valve opening unless: correct line is selected, pressure tests pass, and both sides confirm media/line-up (two-way permissives). • Control static and movement; Electrical bonding of piping/equipment and insulating flange arrangement to prevent arcing during connect/disconnect; • Hose support & movement control: defined operating envelope, saddle/support plan, drift monitoring; incorporate load/movement sensors that trigger ESD-2/PERC before coupler seals are overloaded. • Detect early; contain small releases; Fixed NH_3 detection at manifold (low level) and at vent/processing outlets with alarm/ESD set-points • Hose integrity management; Use metallic/metal-reinforced hoses per ISO 10380 with ammonia-compatible liners/seals; set proof/hydro test, max bend radius, life/retirement and inspection intervals in the HSSE plan
	Loss of ventilation during bunkering	• Ventilation architecture (design); Independent mechanical ventilation for the bunker station sized for ≥30 ACH, low-level extraction and high-level discharge; duty/standby fans with automatic changeover on failure. On NH_3 detection: automatically divert extraction to vapour-processing (scrubber/oxidizer/diffusion) • Loss-of-ventilation interlocks (controls); loss of required ventilation → ESD bunkering (shut transfer pumps/close ESD valves; block re-start until ventilation healthy). Proving: fit airflow/DP switches (or fan speed + damper position + measured ACH) and bring a "Vent OK" permissive into the bunkering C&E and SSL. Powering: feed ventilation controls, gas detection,

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		and ESD logic from essential services; provide UPS for the detection/ESD layer. • Detection & alarms; fixed NH_3 detectors at bunkering station, ventilation discharge, vent-mast outlet, and near HVAC intakes; 25 ppm alarm / 50 ppm automatic shutdown (tie to ESD and ventilation actions). • Access control via airlocks and segregation to minimize crew exposure risks. • Procedures; Pre-bunkering checklist: live ACH read-off, fan auto-changeover test, detector bump, SSL/ESD test, vapour-processing ready (flows, outlet sampling), wind check & abort criteria.
	Static discharge and ignition at manifold (low but non-zero flammability risk: NH_3 LFL≈15%/UFL≈28%)	• Segregation and external placement: Bunkering stations should be on open decks or well-ventilated to avoid vapor build-up • Ex/ignition-source controL; Select all equipment in the bunker station per IEC 60079-20-1 (ammonia data) and class guidance; hot-surface SAT survey during bunkering mode • Static electricity management; Ship/shore interface: adopt insulating flanges per SIGTTO to block stray currents Detection + automatic actions; Fixed NH_3 detection at the manifold (low-level), ventilation discharge, and vent mast outlet, tie to ESD, ventilation boost/divert, and HVAC interlocks. • Ventilation & dilution; Provide ≥ 30 ACH for semi-enclosed stations with low-level extraction and auto-boost/divert to vapour-processing on gas detection • Interface & sequencing; SSL linked-ESD: do not permit opening valves unless ventilation is “healthy, • Portable-equipment discipline: Ban non-Ex battery chargers, lamps, radios at the manifold; control hot-work and use anti-static PPE/footwear in the station. • Water spray / inerting systems: Can suppress vapor or cool potential ignition zones
	Cold-temperature hazards (refrigerated/semi-pressurized): brittle fracture, icing, sensor/valve failure	• Material Integrity & Compatibility; Piping and components must be chosen for ammonia resistance and cold resilience. Set MDMT for all bunker-station wetted parts. • Anti-icing by design; Insulation + heat tracing on manifolds, ERS/valve bodies, low points, drains, and vent/relief discharge stubs where icing can immobilize gear; use heated enclosures for instruments • Cold-service functional integrity; Valve stroking: prove close/open times at low T (consider viscous drag, actuator torque), sensors specify −40 °C (or colder) rated pressure/level/temperature transmitters, Relief & venting - size PRVs using cryogenic methods when two-phase is credible (ISO 21013-3) • Detection Systems: Guidelines require both gas and low-temperature detection, enabling response to cold-related leaks or failures. • Fail-safe Design & Redundancy: Systems must avoid hazardous conditions even in the event of a single failure—including cold-induced malfunctions • Operations & maintenance; Cold-condition SAT (commissioning at temperature): demonstrate valve stroking, actuator heaters, sensor response, PRV heat-tracing, and drain free-flow. Pre-bunkering; verify heat-tracing energized, enclosure temperatures, detector bump, ACH

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		reading, SSL/ESD test; set weather/ambient abort criteria (icing rain, extreme cold
	Effluent & runoff contamination (water-soluble NH_3 from sprays/mist/drains)	• Closed-loop capture & segregation; Coamed, coated drip trays at all credible leak/spray points. Slope to a segregated NH_3 drain header with remotely closable/isolation valves → NH_3 drain tank (level indication + high-level alarm) → vapour-processing (scrubber/combustion/diffusion). No tie-in to general bilge • Processing & vent philosophy; Normal - route contaminated vapour/liquid handling to processing; Emergency venting only via mast • Ventilation + rapid isolation; Semi-enclosed stations: ≥ 30 ACH, low-level extraction, auto-divert to processing/auto-boost on detection; 25 ppm alarm / 50 ppm ESD, integrated with ESD valves and pump stop (≤ 5 s if surge-safe). • Anti-icing & freeze-proof drains; Heat-trace drip trays, drain lines, and water-mist runoff routes so ice doesn't block capture paths • Monitoring & interlocks; Level + HH in NH_3 drain tank; pH/EC at tank outlet or recirculation loop; interlock to block bunkering if drain isolation closed or tank at HH. • Procedural controls; Pre-bunkering evidence pack: drain-tank level OK; isolation valves open; processing unit ready; detector bump; ACH reading; wind/abort criteria; no scupper to sea (blanked/closed).
Storage Tank + Tank Connection Space (TCS) + Transfer Pipes to FPR	Ammonia vapor accumulation in enclosed spaces - TCS/ducts (flammability and toxicity).	• Detection with hard actions (TCS & ducts); Fixed NH_3 detectors in TCS and pipe-enclosure ducts; alarm at 25 ppm; automatic shutdown of master/tank valve at 50 ppm; ≥ 2 detectors per location, with CFD/smoke tests to justify placement. • Ventilation engineered for enclosed ammonia spaces; Independent mechanical extraction, ≥ 30 ACH, low-level and high-level outlets. On ammonia detection, auto-divert ventilation to vapor-processing or auto-dilution/boost to meet exposure limits; document the basis • Loss-of-ventilation = automatic shutdown; loss of ventilation in TCS/ducts/FPR triggers ESD and blocks restart until "Vent OK" permissive is healthy; integrate via Ship–Shore Link when bunkering. • Fast, surge-safe isolation; ESD valves at tank penetrations/TCS boundaries; design for ≤ 5 s close if surge-safe; interlock pump stop → valve close. Log pressure transients at tank nozzles during SAT • Routing to a safe place; Normal blowdown/ventilation discharge to vapor-processing (scrubber/oxidizer/diffusion tank). Use mast only for emergencies and prove no re-ingestion (dispersion/CFD). • Access & segregation; TCS normally unmanned, controlled access, direct to open deck or via airlock; segregated bilge/drain with dedicated holding.
	Toxic NH_3 release (tank penetrations/TCS/annular ducts/piping)	• Fixed detection with hard actions (TCS, annular ducts, pipe enclosures); Install ≥ 2 detectors per location where feasible; alarm 25 ppm (local + CCR) and automatic isolation at 50 ppm (master/tank valve). Add sampling in annular / double-wall ducts and the TCS. • Ventilation engineered for enclosed NH_3 spaces; Provide mechanical extraction (TCS) at ≈ 30 ACH (IGC baseline) with low-level pickups.

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Loss-of-ventilation = automatic shutdown • Fast, surge-safe isolation at tank penetrations; Fit ESD valves at tank nozzles / TCS boundaries; sequence pump stop → valve close, and verify closure time (project target often ≤ 5 s where surge-safe) and pressure transients during SAT • Route to a safe place (treatment first; mast only as emergency) • Segregated drainage & anti-icing; Closed NH_3 drain header from TCS floor sumps / drip trays to dedicated drain tank → processing; • Interfaces that fail safe; Link to ISO 20519-style ship-shore ESD so any TCS/duct alarm or vent-loss trips both sides during bunkering. • Competence & drills; Train crews per DNV RP-0699 on TCS entry controls, SCBA, alarm response (isolate → boost/divert → process), evacuation and ventilation-loss scenarios
	Leaks in vapor lines or tank penetrations causing cold corrosion or frost impact.	• Materials & MDMT discipline (pre-empt brittle fracture); Set an MDMT for all TCS/duct/tank-penetration items equal to the coldest credible metal temperature (flash-vapour conditions near −33 °C for anhydrous NH_3); select austenitic stainless or impact-tested LTCS accordingly; keep Cu/Zn out of NH_3 service • Anti-icing by design; Insulation + heat-tracing, heated cabinets, heat-traced drip trays sloped to segregated NH_3 drain tank → vapour-processing so ice can't block flow paths • Fixed detection with hard actions (TCS, annular ducts, pipe enclosures); ≥ 2 detectors per location, 25 ppm alarm (local + CCR), 50 ppm automatic isolation, duct/annulus sampling. • Ventilation engineered for enclosed NH_3 spaces; Independent extraction at ≈ 30 ACH • Loss-of-ventilation = automatic shutdown • Fast, surge-safe isolation near the tank; ESD valves at penetrations/TCS boundaries; sequence pump stop → valve close; verify closure times (target ≤ 5 s if surge-safe) and pressure transients during SAT. • Relief/vent handling that won't freeze up • Elastomers & instruments that still work cold; Specify PTFE/EPDM/FFKM/HNBR (qualified) for seals; avoid FKM/Viton in anhydrous NH_3; select instruments rated to −40 °C (or colder); heat-trace impulse lines
	Overpressure or vacuum scenarios from thermal variation or vent failures.	• Tank pressure envelope (both sides of zero): Primary control, Overpressure protection, Vacuum protection protect tanks from thermal variation effects.) • Blocked-vent & failure detection; Vent proving: differential-pressure or airflow switches across P/V valves, vent headers, and duct extractions; "Vent OK" permissive to allow transfer. PRV/vent health: heat-trace/ice shielding on PRV outlets and vent stubs; outlet NH_3 monitoring port to confirm treatment efficacy/dispersion assumptions • Fast, surge-safe isolation (limit pressure excursions): ESD valves at tank penetrations and TCS boundaries; sequence pump stop → valve close, with demonstrated close time (target ≤ 5 s if surge-safe) • Line & trapped-liquid thermal relief: Thermal-relief valves from all liquid-full, isolable sections

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		(valves/low-spots/annular spaces) to vapor-processing, not to deck. Prevents overpressure from sun/ambient swings when isolated. • Enclosed-space ventilation & routing: TCS/ducts: extraction ≈ 30 ACH (IGC baseline) with low-level pickups; on NH_3 detection, auto-boost and/or divert discharge to vapor-processing. Treat loss-of-ventilation ⇒ ESD and block restart until "Vent OK." • Detection & levels (overfill tie-in); Fixed NH_3 detection, Independent tank level
	Material degradation from ammonia's corrosive nature.	• Metal selection / MDMT discipline; Ban brass/bronze, zinc and mercury in wetted parts. Use austenitic stainless or carbon steel that meets MDMT. • Elastomer/seal policy; Standardize EPDM or PTFE for seals, gaskets, valve seats, and hoses in contact with anhydrous NH_3 • Galvanic/crevice control; Use isolation kits (gaskets/sleeves) between dissimilar metals; specify coatings (e.g., epoxy phenolic) inside NH_3-exposed sumps/cofferdams; • Drainage & processing (limit wet NH_3 contact); Closed NH_3 drain header → dedicated drain tank → vapour-processing; no tie-in to general bilge. • Detection + rapid isolation (limit exposure time); Fixed NH_3 detection in TCS/ducts (25 ppm alarm / 50 ppm ESD), linked to ESD valves at tank penetrations (≤ 5 s if surge-safe). • Cold-service integrity; Insulation + heat tracing for nozzles/valves/sensors to prevent frost-jacking and seal embrittlement; • Inspection & monitoring; Introduce thickness monitoring on carbon-steel spools in cold/wet zones; periodic seal/seat inspections; maintain a materials register (wetted parts + elastomers) with change control.
	Detection & ESD failure (fault tolerance, voting, placement)	• NH_3 detection architecture (fault-tolerant); Set-points, Voting - TCS & ducted runs adopt 2oo3 voting while Tight spaces/annular ducts: at least 1oo2 (two sensors on independent taps), Placement proven by physics: justify detector heights & spacing using CFD or smoke-release tests, Self-diagnostics & keep-alive, Power resilience: detectors and logic on essential power with UPS to ride through voltage dips. • Ventilation & routing (make detection consequential); Independent extraction in TCS/ducts at ≈ 30 ACH, ammonia alarm: auto-boost and/or divert discharge to vapour-processing (scrubber/oxidizer/diffusion tank). Treat loss-of-ventilation as ESD, • ESD logic & valves (fail-safe); Cause-and-Effect: 25 ppm → alarm (local/door/CCR) and ventilation boost; 50 ppm → pump stop + close tank/master valves (target ≤ 5 s if surge-safe); interlock restart to Vent OK + Gas < alarm. Segregation & diagnostics: dual power feeds/UPS to ESD PLC I/O, separate field cables from detectors on different routes. Interfaces: tie trips into Ship-Shore Link (SSL): any TCS/duct alarm or vent-loss stops both sides during bunkering/transfer. • Drains & processing (contain consequences of any miss); Closed NH_3 drains from TCS floors/drip trays to a dedicated drain tank → vapour-processing; detect at drain-tank vent; no connection to general bilge.
	External fire impingement /	• Keep the vessel cool / protected; Water-spray deluge over

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
	BLEVE (Fully pressurized)	exposed pressurized fuel tanks, domes/penetrations, manifolds, TCS-facing boundaries per IGC precedent: ≥10 $L \cdot m^{-2} \cdot min^{-1}$ (horizontal) and ≥4 $L \cdot m^{-2} \cdot min^{-1}$ (vertical). PFP or shielding for tank skirts/penetrations, TCS bulkheads, supports, and vulnerable appurtenances where deluge shadowing is likely. • Control pressure on both timelines (slow heat-up & emergency); PRVs sized for fire case (and other credible scenarios) per ISO 21013-3; cold-service certified. Emergency depressurization (EDP) option: evaluated path to processing. • Stop escalation fast; ESD logic (ABS practice): pump stop → master/tank valves close (target ≤5 s if surge-safe); interlock restart to Vent OK, deluge available, Gas < alarm. Detection-driven actions (BV): fixed NH_3 detection at TCS/ducts with 25/50 ppm actions; loss-of-ventilation ⇒ ESD; ventilation boost/divert to processing on alarm. • Fire systems integration; Automatic fire detection around tank/TCS with deluge auto-start and HVAC isolation; deluge & firemain on essential power + remote start outside hazard zone (IGC).
	Cryogenic brittle fracture/icing (refrigerated/Semi-pressurised)	• Materials & MDMT discipline (prevent brittle fracture); Assign an MDMT for all tank penetrations, TCS spools, supports and annular/duct hardware equal to the coldest credible metal temperature (flashing NH_3 near −33 °C at 1 bar). Select austenitic stainless or impact-tested LTCS accordingly; exclude Cu/Zn alloys in wetted service • Anti-icing by design; Insulate + heat-trace vapour lines, nozzles, PRV/vent stubs, drains/low points and valve/ERS bodies; use heated cabinets for transmitters/actuators. Provide heat-traced, sloped drip trays to a dedicated NH_3 drain tank → vapour-processing so ice cannot trap liquid/vapour. • Cold-service functional integrity; Specify instruments/actuators rated to −40 °C (or colder) • Ventilation for enclosed NH_3 spaces (TCS/ducts); Independent extraction ~ 30 ACH with low-level pickups; on NH_3 alarm, auto-boost and/or divert discharge to vapour-processing. Treat loss-of-ventilation ⇒ ESD and block restart until “Vent OK.” • Detection with hard actions; Fixed NH_3 detectors in TCS and annular/pipe enclosures • Relief & venting that still works cold; PRVs sized per ISO 21013-3 • Elastomer/internals fit for NH_3 & cold; Standardise EPDM/PTFE (or OEM-proven FFKM/HNBR) for seats/gaskets/hoses; avoid FKM/Viton in anhydrous NH_3 unless supplier provides qualified data. • Operations & drills; Cold-condition SAT before first bunkering; pre-transfer checks include tracing “healthy”, cabinet set-points, detector bumps, ACH read-off, and processing readiness. Train crews to DNV RP-0699 (icing, SCBA entry, abort/restart rules)
	Static electricity & ignition control	• Ex selection & hot-surface control; Specify Ex equipment using IEC 60079-20-1 data for ammonia; select with a T-class margin (T1 ceiling; prefer lower surface temps). Require a hot-surface survey in TCS/FPR transfer modes. • Static-electricity management; Ship/shore interface: fit insulating flanges (or non-conductive hose sections) at the interface. System bonding/continuity: document bonding of tanks, TCS spools and vapour lines; specify hose/arm electrical characteristics and continuity checks

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Detection with hard actions; Fixed NH_3 detection in TCS, ducts/annuli, FPR interface: • Ventilation & routing; Independent extraction in TCS/ducts (use ≈ 30 ACH cargo-code baseline), low-level pickups; on any alarm, boost/divert to vapour-processing (scrubber/oxidizer/diffusion tank). Treat loss-of-ventilation ⇒ ESD • ESD logic & SSL; Cause & Effect: 25 ppm → alarm/boost; 50 ppm → pump stop + close ESD valves (≤ 5 s if surge-safe). Interlock restart to Vent OK and Gas < alarm. Tie trips into linked ship/shore ESD (ISO 20519) so both sides stop. • Portable-equipment discipline; Ban non-Ex portables (chargers, lamps, radios) in TCS/FPR; confirm via pre-transfer checks and permit-to-work. (Policy gap in public rules—close via owner SMS/port permit aligned to ISO 20519 workflows.)
	Effluent/runoff contamination from sprays, drains, cofferdams	• Closed-loop capture & segregation; Coamings/drip trays/sumps in TCS and around penetrations; sloped, heat-traced, coated drains → dedicated NH_3 drain header → NH_3 drain/holding tank (level & HH alarms) → vapour-processing (scrubber/oxidizer/diffusion tank). No connection to general bilge. • Monitoring & interlocks; Level + HH in the NH_3 drain tank; pH/EC monitoring at outlet or recirculation; ESD/transfer inhibit if HH, if drain isolation is closed, or if processing is not "Ready." • Ventilation & rapid isolation; TCS/ducts: extraction ≈ 30 ACH (IGC baseline) with low-level pickups; on NH_3 alarm: auto-boost/divert to processing; treat loss of ventilation ⇒ ESD. Fast ESD at tank penetrations (target ≤ 5 s if surge-safe) to limit effluent generation. • Processing & vent philosophy; Normal handling to processing; emergency venting by mast only with no-re-ingestion evidence (CFD/tracer) for accommodation/HVAC intakes. Provide outlet sampling on processing/mast. • Freeze-proof drains & cofferdams; Heat tracing/insulation for drains, sumps, and cofferdam low points; avoid ice-blockage that traps contaminated water and releases vapour later. • Procedures & permits; Pre-transfer evidence pack (ISO 20519 workflow): drain path lined-up, drain-tank level OK, pH/EC online, processing "Ready," detectors bumped (25/50 ppm), ACH healthy, wind/abort criteria set; SSL/linked-ESD tested.
	Vent mast recirculation toward accommodation air intakes	• "Processing-first" routing; mast as emergency; Route normal blow-off/ventilation to vapour-processing (scrubber/oxidizer/diffusion tank). Reserve mast for emergency/abnormal cases. • Vent-mast siting & geometry (design to avoid re-ingestion) e.g applying BV numeric siting: outlet ≥ B/3 or 6 m above deck (whichever higher) and ≥ B or 25 m (whichever less) from any HVAC intake or opening to accommodation/Service spaces. OR use IGC 10 m as a minimum stand-off benchmark where BV values are not practicable, then prove equivalency by CFD. • Proof of "no re-ingestion" (analysis + testability); Perform CFD dispersion under worst winds/headings, stability classes, and combined release profiles (steady PRV, pulsed, cold dense plume). Document NH_3 concentration envelopes at HVAC intakes and work areas; adjust mast height/orientation as needed • HVAC & ventilation interlocks (make analysis consequential); Fit NH_3 detectors at accommodation intakes and auto-isolate or switch to recirc/closure on detection or on mast-

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		release permissive active; bias positive-pressure on critical control rooms. • Wind-aware permissives; Add a “Wind OK” permissive (sector-based wind sensor logic) that inhibits any non-emergency mast vent when wind would drive plume toward intakes; fall back to processing route • Detection & ESD to shorten events; Fixed NH_3 detection in TCS/ducts with 25 ppm alarm and 50 ppm automatic shutdown (tank/master valves). This reduces the magnitude/duration of releases that could load the mast. Fast isolation (ABS practice): pump stop → ESD valves close • Outlet monitoring & sampling; Provide a sampling/monitor port on processing discharge and, where practicable, at the mast base
	Inerting/purging failure (TCS or annular/interbarrier spaces)	• Define an inerting philosophy (TCS & annular spaces) e.g Targets: maintain $O_2 \leq 8$–10 vol % in annular/duct spaces during operation and a slight positive N_2 purge or verified extraction so leaked NH_3 is swept to treatment. • N_2 supply that can’t quietly fail; Two independent sources (ship N_2 generator + high-pressure bottles or dual N_2 gensets), auto-changeover, purity (≥ 95–99.5 %) and pressure monitoring with alarms. Loss-of-inerting = ESD: any O_2 high / N_2 pressure low / flow low trip → stop transfer + close tank/master valves • Ventilation engineered for enclosed spaces (TCS/ducts); Extraction ≥ 30 ACH (IGC baseline) with low-level pickups; on NH_3 detection, boost and/or divert discharge to vapour-processing; treat loss-of-ventilation as ESD and block restart until “Vent OK.” • Detection with hard actions; Fixed NH_3 detection in TCS & annular/pipe enclosures; 25 ppm alarm (local/door/CCR) and 50 ppm automatic isolation of master/tank valves per BV. Consider at least 1oo2 sampling in long annuli. • Routing to a safe place; Normal purged streams/extraction discharge to vapour-processing (scrubber/oxidizer/diffusion tank). Use vent mast only for emergency and prove no re-ingestion (dispersion/CFD) to accommodation intakes. • Purge/pressurization of enclosures; For any instrument cabinets in TCS/annulus services, apply IEC purge/pressurization practice • Procedures & permits (ship–shore integration); Use ISO 20519-style SSL / linked-ESD workflow for pre-transfer evidence packs until an NH_3-specific interface standard lands
	Transfer line surge/hammer to FPR (valve stroking, isolation of liquid-full sections)	• Engineered ESD sequencing (surge-safe); Sequence: pump stop → controlled valve close at tank penetrations/FPR inlets; use closure ramps (e.g., split-range 80% fast / 20% slow) or S-curve profiles to limit pressure rise. • Hydraulic-transient analysis & acceptance; Perform time-domain surge analysis on the entire TCS→FPR transfer, covering pump trip/start, power dip, ESD-1/ESD-2, check-valve slam, valve mis-stroke, and isolation of liquid-full legs. • Surge-control hardware; Gas-cushion surge vessels / accumulators, Anti-slam check valves, Bypass equalization, VFD/soft-starter profiles for pump • Thermal-expansion relief of trapped liquid; Install thermal relief valves from every isolable liquid-full section to a closed relief header → vapour-processing • Valve & actuator capability; Specify stroke-time control, fail-close rate-limiting, low-

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		temperature ratings, and partial-stroke test features. Verify closure time vs. surge during SAT (instrumented). • Structural integrity for dynamic loads; Pipe supports/restraints (guides, snubbers) sized to transient forces from the surge model • Detection/ESD & ventilation context (limit consequences); Maintain BV set-points in TCS/annuli (alarm 25 ppm, auto-shutdown 50 ppm) and extraction ventilation (~30 ACH) so any leak during a surge event is short and quickly diluted/processed.
Fuel Preparation room + Transfer to engine room	Ammonia leakage in enclosed FPR → flammable and toxic cloud.	• Fixed detection with hard actions (FPR & enclosures); NH_3 detectors in FPR, at doorways, and in double-walled/ducted runs entering/exiting the room. Alarm at 25 ppm and automatic isolation at 50 ppm. • Ventilation engineered for enclosed ammonia rooms; Independent extraction, target ≈ 30 ACH (IGC connection-space yardstick) with low-level pickups. On NH_3 alarm: auto-boost and/or divert discharge to vapour-processing (scrubber/thermal oxidizer/diffusion tank). Treat loss-of-ventilation as ESD and block restart until "Vent OK" • ESD sequencing (surge-safe); Cause-and-Effect: 25 ppm → alarm & ventilation boost; 50 ppm → pump stop → close ESD valves • Processing-first routing; mast only for emergency; Normal blow-off/ventilation gas from FPR fans and purges goes to vapour-processing; if a mast is retained for emergency, provide "no re-ingestion" evidence (CFD/tracer) to accommodation/HVAC intakes. • Segregated drains & cold-service integrity; Closed NH_3 drain header → dedicated drain tank → processing (no general bilge). Insulate/trace low points and actuator cabinets to prevent frost-lock that prolongs a leak. • Ex equipment & hot-surface discipline; Select electricals per IEC 60079-20-1 (AIT→T-class; T1 ceiling 450 °C—choose lower surface-temp equipment where practicable). Ban non-Ex portables in FPR. • Interfaces that fail safe; Link FPR trips into Ship–Shore Link (ISO 20519) during bunkering/commissioning transfers: any FPR alarm/vent-loss stops both sides. • Competence & drills; Train crews per DNV RP-0699: SCBA entry, toxic cloud response, HVAC isolation, muster/evac, restart criteria
	Cold burn risks from liquid release or frost contact.	• Cold-service integrity; Insulate + heat-trace all FPR liquid/vapour lines, manifolds, PRV stubs, drains/low-points, valve bodies and transmitters. Use heated cabinets for actuators/instruments; • Fixed detection with hard actions; NH_3 detectors in the FPR, at doorways, and in double-walled/ducted runs; 25 ppm alarm and 50 ppm automatic isolation • Ventilation engineered for enclosed rooms; Independent extraction, target ≈ 30 ACH with low-level pickups; on NH_3 alarm, auto-boost and/or divert to vapour-processing. Treat loss-of-ventilation as ESD and block restart until "Vent OK." • ESD sequencing (surge-safe); Cause & Effect: 25 ppm → alarm & boost; 50 ppm → pump stop → close ESD valves (project target commonly ≤ 5 s if surge-safe). Validate closure profiles vs. transient pressure limits

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Segregated drainage & processing-first routing; Coamings/drip trays/sumps in FPR sloped to closed NH_3 drain tank → vapour-processing; no tie-in to general bilge. Normal ventilated/purged streams route to processing; mast only for emergency with "no re-ingestion" evidence. • Emergency showers & eyewash + PPE; Install plumbed emergency shower & eyewash inside or immediately outside the FPR with unobstructed access; mark on the muster plan. Stock splash-protective suits, chemical gloves, face-shield/goggles; for unknown/toxic atmospheres use SCBA • Materials & elastomers; Use austenitic stainless/LTCS suitable for the project MDMT; standardize EPDM/PTFE (or OEM-proven FFKM/HNBR) for cold-service seals; • Competence & drills; Train crews per DNV RP-0699 on cold-injury response: buddy rescue, SCBA entry, 15-minute water flush,
	Vapor migration into adjacent crew spaces if not isolated properly.	• Gas-tight zoning & pressure regimes; Treat the FPR as a gas-dangerous enclosure relative to adjacent crew spaces.Provide gas-tight boundaries and self-closing doors;use an IGC-style airlock and held at overpressure to the hazardous side). No direct door from safe to hazardous. • Ventilation engineered to contain & dilute; Independent extraction for the FPR, target ≈ 30 ACH with low-level pickups. Route exhaust to vapour-processing on alarm. Loss-of-ventilation ⇒ ESD • HVAC intake protection for accommodation/control rooms; Fit NH_3 detectors at accommodation/CCR intakes; on detection, auto close dampers / stop fans / switch to recirc, and maintain positive pressure in CCR/critical rooms. • Detection with hard actions in/around the FPR; Fixed NH_3 detection in the FPR, at doors/airlock, and in double-walled/ducted runs. Thresholds (25 ppm alarm / 50 ppm automatic isolation: close tank/master/FPR isolation valves; stop pumps • ESD sequencing (surge-safe) to prevent spread; Cause & Effect: 25 ppm → alarm & ventilation boost; 50 ppm → pump stop → close ESD valves • Exhaust/vent stand-off from intakes; Keep any hazardous exhaust/vents ≥ 10 m from intakes/openings (IGC), and follow BV's more detailed siting for mast releases where relevant; demonstrate no re-ingestion by dispersion analysis/CFD. • Boundaries & openings quality; For superstructure sides facing fuel areas, apply A-60 integrity and closing devices on any air inlets/outlets; • Operations & competence; Embed pre-transfer evidence packs (ACH healthy; intake-detector bumps; HVAC auto-closure test; SSL/linked-ESD test; processing "Ready"). Train crews to DNV RP-0699 (toxic gas migration scenarios, HVAC isolation, muster routes)
	Pump or piping failure under corrosive exposure.	• Right materials, everywhere; For wetted metallics: Austenitic stainless (300 series) or suitable LTCS; ban Cu/Zn (brass/bronze) in any wetted service. Elastomers & seats: standardize PTFE / EPDM for NH_3. Pump/seal strategy that tolerates NH_3; Prefer sealless (canned-motor or magnetic-drive) pumps for toxic service. If mechanical seals are used, specify API 682 Plan 74 (dual pressurized N_2 barrier dry-gas seal) with leakage monitoring routed to vapour-processing

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Detection & rapid isolation (limit consequences); Fixed NH_3 detection in FPR/penetrations: 25 ppm alarm; 50 ppm → stop pumps + close master/tank/FPR ESD valves • Ventilation & routing; Independent extraction ≈ 30 ACH with low-level pickups; on alarm boost and divert discharge to vapour-processing; treat loss-of-ventilation ⇒ ESD • Drains & containment; Scuppers/drip trays sloped to dedicated NH_3 drain tank → processing; no tie-in to general bilge. (BV processing-first philosophy.) • Condition & integrity monitoring; Seal-gas panel pressure/flow alarms (Plan 74), bearing temps, vibration on pumps; pH/EC in drain tank to catch early product ingress from corrosion. • Procurement QA; PMI for wetted metallics; elastomer certification against NH_3; vendor materials lists show zero Cu/Zn in wetted paths
	Liquid pooling / cryogenic or hot process hazards	• Keep liquid off the deck — capture, segregate, treat; Coamings/drip trays/sumps under pumps, filters, vaporizers, valve skids; sloped & coated with heat-traced drains to a dedicated NH_3 drain tank (level H/HH) → vapour-processing (scrubber/oxidizer/diffusion tank). No connection to the general bilge. Online monitoring: pH/EC on the drain tank (early indication of NH_3 ingress); HH of drain tank ⇒ inhibit transfer/ESD in the C&E. • Detect and stop fast — limit the pool; Fixed NH_3 detection in FPR and penetrations: 25 ppm alarm, 50 ppm automatic isolation. ESD sequencing (surge-safe): pump stop → profiled ESD closures; verify stroke profiles against transient limits • Ventilate & route to a safe place; Independent extraction for FPR, target ≈ 30 ACH with low-level pickups; on NH_3 alarm auto-boost and/or divert exhaust to processing. Treat loss-of-ventilation as ESD with restart inhibited until “Vent OK.” • Handle temperature extremes; Cold integrity: insulate + heat-trace cold-susceptible item. Hot-surface control: specify Ex equipment by IEC 60079-20-1 (AIT→T-class); perform a hot-surface survey. • Prevent trapped-liquid overpressure; Fit thermal-expansion relief on all isolable liquid-full sections to a closed relief header → processing; • Human protection; Emergency shower & eyewash at or just outside FPR access; SCBA and cold-injury PPE (face shield/goggles, chemical gloves)
	Failure of inerting/purging in double-walled pipes / systems	• Define annulus performance targets; Normal mode: annulus kept under extraction (≥30 ACH) or N_2 purged with verified low O_2 • N_2 supply that can’t quietly fail; Provide two independent N_2 sources (generator + bottle rack or dual gensets), auto-changeover, purity/pressure/flow monitoring with alarms, and barrier check valves. Loss-of-inerting (O_2 high / N_2 low / flow low) ⇒ ESD • Annulus monitoring & trips; Fit O_2 analyzers (continuous) and NH_3 detectors. Trips at O_2-High and NH_3-Present drive: vent boost or N_2 flood, then ESD if not cleared. • Ventilation engineered for enclosed fuel spaces; Independent extraction ≈ 30 ACH in FPR with low-level pickups; on any NH_3 alarm: auto-boost and divert exhaust to vapour-processing; treat loss-of-ventilation ⇒ ESD with restart interlocks (Vent OK/Gas < alarm) • Routing to a safe place (processing-first); Normal annulus/room exhaust → vapour-processing (scrubber/oxidizer/diffusion tank). Reserve mast for emergency and keep “no re-ingestion”

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		evidence (dispersion/CFD) for accommodation intakes. • Cause & Effect (surge-safe); 25 ppm (room) → alarm, vent boost/N_2 flood annulus; 50 ppm (room) or O_2-High / N_2-Low (annulus) → pump stop → ESD valves close • Purge/pressurization of local enclosures; Where analyzers, junction boxes or valve cabinets sit in/serve the annulus, apply IEC 60079-2 purge/pressurization • Ops & ship–shore integration; Use ISO 20519-style checklists & linked ship/shore ESD (SSL) so annulus trips stop both sides during transfers/commissioning.
	Ignition and electrostatic risks (even with narrow flammability)	• Ex selection & hot-surface control; Select electrical/rotating equipment per IEC 60079-20-1; document a T-class margin and perform a hot-surface survey with equipment at bunkering/operation loads. • Static-electricity management; Interface policy: adopt insulating flanges or non-conductive hose sections at ship/shore; no bonding wires. Room/system continuity: bond tanks, skids, and spools; specify hose/arm electrical properties and add continuity test points with pre-transfer checks logged. • Ventilation engineered for enclosed FPRs; Independent extraction ~≥30 ACH with low-level pickups; on NH_3 alarm auto-boost and divert exhaust to vapour-processing; treat loss-of-ventilation as ESD • Detection + hard actions; Fixed NH_3 detection in FPR, doorways, and double-walled runs: 25 ppm alarm and 50 ppm automatic isolation. • ESD sequencing (surge-safe); Cause & Effect: 25 ppm → alarm/boost; 50 ppm → pump stop → profiled ESD closures. Tie trips into SSL so the shore side stops, too • Portable-equipment discipline; Ban non-Ex portables (lamps, chargers, radios) in FPR; enforce via pre-transfer checks and permit-to-work logged to the evidence pack • Routing & containment; Normal blow-off/purges to vapour-processing; emergency venting via mast only with CFD “no re-ingestion” evidence to accommodation intakes. Provide coamings/trays → NH_3 drain tank (segregated from bilge)
Engine room	Ammonia leaks into hot engine atmosphere → flashback or toxic exposure.	• Fixed detection with hard actions (room + intakes + enclosures); Install NH_3 detectors near potential leak sources at engine-room HVAC intakes, and inside relevant cabinets/ducts. • ESD sequencing that is surge-safe; Cause & Effect: 25 ppm → alarm; 50 ppm → pump stop → close ESD valves • Ventilation & zoning; Maintain strong extraction around fuel interfaces/engine enclosures; use IGC’s ≥ 30 ACH benchmark for adjacent connection spaces. Route alarm exhaust to vapour processing where practicable; treat loss-of-ventilation ⇒ ESD with restart only on Vent OK. • HVAC intake protection (stop toxic ingress); Fit NH_3 sensors at ER/accommodation intakes; on trip, auto-close dampers / stop fans / switch to recirc, and maintain CCR positive pressure to prevent migration. • Ex selection & hot-surface control; Select electrical/rotating kit via IEC 60079-20-1; document T-class margin vs NH_3 AIT and perform a hot-surface survey with the engine at representative

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		loads • Double-wall to the engine + annulus integrity; Use double-walled piping into the ER with annulus extraction or N_2 purge and annulus NH_3/O_2 monitoring; make loss-of-inerting/vent ⇒ ESD. • Processing-first philosophy; mast only for emergency; Direct purged/vented streams to scrubber/oxidizer/diffusion tank only emergency go to mast—and keep dispersion proof (no re-ingestion at intakes) • Drains/containment; Provide coamings/trays under skids and slopes to a dedicated NH_3 drain tank (H/HH with ESD inhibit) → vapour processing; no general bilge cross-connections • Operations & competence; Drill toxic-first response (SCBA, muster, HVAC isolate) and engine transition/shutdown on gas trip per DNV RP-0699.
	Vapour accumulation/migration via ventilation	• Detect early & act hard (room + intakes + enclosures); Place NH_3 detectors at likely sources, engine-room HVAC intakes, and sub-enclosures/ducts. Adopt BV thresholds: 25 ppm alarm (local/bridge/ER) and 50 ppm automatic isolation. • ESD sequencing (surge-safe); C&E: 25 ppm → alarm & ventilation boost; 50 ppm → pump stop → ESD valves close, with stroke profiles validated by transient analysis. Integrate engine OEM trips (e.g., switch to pilot-only / shutdown). • Ventilation & zoning engineered to prevent migration; Provide strong extraction at fuel interfaces/ER sub-enclosures; use ≥ 30 ACH as a design yardstick (IGC precedent). Route alarm exhaust to vapour-processing where practicable; treat loss-of-ventilation ⇒ ESD with restart only on “Vent OK.” • HVAC intake protection for ER & accommodation; Fit NH_3 sensors at intakes; on trip, auto-close dampers / stop fans / switch to recirc and hold CCR positive pressure to stop migration into manned spaces. • Double-wall penetrations + annulus integrity; For lines entering ER, use double-wall with annulus extraction or N_2 purge and O_2/NH_3 monitoring; loss-of-inerting/vent ⇒ ESD • Ex selection & hot-surface discipline; Select per IEC 60079-20-1; maintain a T-class margin and run a hot-surface survey at representative engine loads • Processing-first routing; mast only for emergency; Normal purged/vented streams go to scrubber/oxidizer/diffusion tank; • Drains/containment (avoid secondary emissions); Coamings/trays under skids; segregated NH_3 drain tank (H/HH) → processing; no general bilge tie-ins. • Ops & competence; Drill HVAC isolation / toxic-first response / SCBA entry per DNV RP-0699;
	Overpressure/abnormal pressure or thermal expansion in fuel system	• Thermal-expansion relief on every isolable liquid-full section; Fit thermal relief valves from each blockable leg to a closed relief header → vapour-processing (scrubber/oxidizer/diffusion tank). • Engineered ESD sequencing (surge-safe); Cause & Effect: gas present (≥ 50 ppm) or over-pressure logic ⇒ pump stop → profiled ESD-valve closure, verified by transient (water-hammer) analysis so you don’t create secondary over-pressure.

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Surge control hardware; Where analysis shows peaks > limits, add surge vessels/accumulators, anti-slam checks, recirc/bypass equalization, and VFD ramps/coast-down profiles for pumps. • PSV/PRD strategy & disposal; Provide PRVs at equipment subject to heat-soak/hot surfaces; route all relief streams to a closed system • Ventilation & zoning around fuel interfaces; use extraction ≥ 30 ACH (IGC yardstick) with auto-boost on alarm; treat loss-of-ventilation ⇒ ESD and interlock restart to "Vent OK." • Detection with hard actions; Room + intake NH_3 detection: 25 ppm alarm, and 50 ppm automatic isolation. • Intake protection (stop migration during relief events); Fit NH_3 sensors at ER/accommodation intakes; on trip, close dampers / stop fans / recirc, maintain CCR positive pressure. • Drains & containment; Coamings/trays under fuel skids; slope to dedicated NH_3 drain tank (H/HH interlocked) → processing; no general bilge tie-ins.
	Ammonia combustion misfire or pilot-fuel failure risking emission or flame propagation.	• Engine-control logic for misfire/pilot failure; Per-cylinder misfire detection → instant ammonia-injection cutback/shutdown on the affected cylinders; auto transition to pilot-only or engine shutdown per OEM limits. • NH_3 slip & room detection with hard actions; room/duct/intake NH_3 detectors at 25 ppm alarm and 50 ppm automatic fuel isolation. Add stack NH_3 slip monitor to detect post-combustion slip rise during misfire, triggering load reduction/transition • ESD sequencing (surge-safe) • Ventilation & zoning for fuel sub-enclosures • HVAC intake protection; NH_3 sensors at ER/accommodation intakes; on trip, auto damper closure / fan stop / recirc, keep CCR positive pressure to prevent toxic migration during misfire-driven releases/purges. • Routing to a safe place (processing-first) • Ex selection & hot-surface discipline; Select electrical/rotating kit via IEC 60079-20-1 (AIT→T-class); hot-surface survey • Double-wall to engine + annulus integrity; annulus extraction/N_2 purge and annulus NH_3/O_2 monitoring; loss-of-inerting/vent ⇒ ESD. • Operations & competence; Crew trained to DNV RP-0699 for toxicity-first response, SCBA entry, engine transition/shutdown on misfire, HVAC isolation, and restart criteria; incorporate ship–shore link
	Difficulty detecting ammonia fires (invisible blue flame).	• Layered fire detection tuned for "invisible" flames; Install UV or UV/IR flame detectors proven for inorganic/faint flames at potential ignition points. Add visual flame detection (video analytics) pointing along machinery skid aisles. Retain smoke/heat where suited, but treat them as secondary (NH_3 fires can be low-soot). • Gas detection with hard actions (toxicity-first); NH_3 detectors: 25 ppm alarm; 50 ppm ⇒ stop NH_3 pumps + close master/fuel ESD valves

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Ventilation & intake protection; Provide strong extraction around fuel sub-enclosures; loss-of-ventilation ⇒ ESD. • Ex selection & hot-surface discipline; Select per IEC 60079-20-1 and perform a hot-surface survey at representative loads to minimize secondary ignition around a nascent flame. • Routing to a safe place (processing-first); Purges/relief streams during response go to scrubber/oxidizer/diffusion tank; keep any mast path supported by dispersion “no re-ingestion” evidence • Human-machine interface & alarms; Distinct tones/strobes for UV/UVIR fire vs NH_3 gas alarms; camera thumbnails and detector IDs on ER mimic to speed localization.
	Corrosive degradation of engine components exposed to ammonia.	• Materials discipline (eliminate the chemistry); For any wetted service (fuel skids, injectors, lines, valves, instruments): ban Cu/Cu-alloys and Zn; use 300-series SS or suitable carbon/LTCS proven for NH_3; avoid galvanic couples introducing Cu/Zn. Elastomers/seats: standardize PTFE / EPDM; avoid FKM/Viton unless a vendor qualifies a specific grade for NH_3 • Environmental control (stop the electrolyte); Ventilation at fuel sub-enclosures: adopt ~≥ 30 ACH • Detection with hard actions (cap consequences) • Condensate/effluent management; Coamings/trays under skids; slope to dedicated NH_3 drain tank → vapour processing • Seal strategy; Prefer sealless pumps (canned/mag-drive) in toxic service; otherwise use dual seals with inert barrier and leak-return to processing; • Surface protection & isolation; Coat carbon-steel housings/supports near ammonia equipment; splash shields around flanged joints; thermal insulation to avoid NH_3-rich condensation on cold spots. • Monitoring; PMI of wetted metallics; materials ledger proving zero Cu/Zn in wetted path. • Intake protection; Intake NH_3 detectors → auto damper closure / fan stop / recirc; keep CCR positive pressure to avoid drawing corrosive vapour/aerosol into control rooms • OEM integration; Link engine ECU alarms (e.g., cylinder misfire/slip rise) to cut ammonia, transition to pilot-only, and trigger room isolation to reduce continued exposure
	Fire protection & firefighting compatibility	• Agent selection & layering (fit for NH_3); Primary control in ER: local-application water-mist/spray to cool, dilute and knock down vapors around fuel skids/enclosures; scale up to deluge only in defined zones. Small flame knock-down: provide NH_3-rated dry-chemical (fixed/portable) and CO_2 portables for incipient fires. Foam: if specified, use alcohol-resistant/regular foam only for secondary fuels/lubricants; foam has limited value on gaseous NH_3 itself. • Gas-first hard actions (limit the fire’s fuel); Fixed NH_3 detection • HVAC intake protection & zoning; NH_3 sensors at ER & accommodation intakes → auto damper close / fan stop / recirc; keep CCR positive pressure so water-mist “steam-out” or NH_3 vapor doesn’t migrate. • Ventilation performance; strong extraction (≈≥30 ACH) with auto-boost on gas/fire alarm;

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		treat loss-of-ventilation ⇒ ESD. • Effluent & runoff management; Coamings/trays under skids; slope to a segregated NH_3 drain/KO tank with pH/EC monitoring → vapour processing. • Cause & Effect (C&E) tying it together; NH_3 ≥50 ppm (or Fire detected) ⇒ stop NH_3 pumps → close ESD valves (surge-safe) → enable local water-mist, boost extraction, close intakes, route purges to processing; log times. • Ex/T-class & hot-surface control; Select equipment by AIT → T-class; run a hot-surface survey at load • Crew competence & drills; Drill toxicity-first response (SCBA, muster), agent selection, intake isolation, and post-fire decon/runoff handling per DNV RP-0699.
	Ignition & electrostatic (flammability is narrow but credible)	• Ex selection & hot-surface control; Select per IEC 60079-20-1; document T-class margin and run a hot-surface survey at representative engine loads. • Static-electricity management; Interface policy: insulating flange / electrically discontinuous hose, no bonding wire at ship/shore; keep each side internally continuous. Onboard continuity: specify hose/arm resistance range; add continuity test points; include pre-operation checks in the evidence pack. Onboard continuity: specify hose/arm resistance range; add continuity test points. • Ventilation engineered for ER fuel sub-enclosures/ducts; Independent extraction targeting ≥ 30 ACH with low-level pickups; on gas alarm, auto-boost and (where practicable) divert exhaust to processing; treat loss-of-vent ⇒ ESD • Gas detection with hard actions; Place NH_3 detectors at leak sources, • Cause & Effect (surge-safe); 25 ppm → alarm & vent boost; 50 ppm → pump stop → ESD valve close; tie into SSL so shore stops too. • Routing & containment; purges/blow-offs to vapour-processing (scrubber/oxidizer/diffusion tank); retain an emergency mast only with no-re-ingestion evidence to ER/accommodation intakes. Provide coamings/trays → segregated NH_3 drain tank → processing • Portable-equipment discipline; Ban non-Ex portables in ER ammonia areas during operations • Competence & drills; Train per DNV RP-0699: ignition control, SCBA entry, HVAC isolation, ESD/SSL drills, restart criteria
	Effluent/drain management (NH_3-contaminated liquids, mist/condensate, wash-down, water-screen runoff).	• Closed-loop liquid handling; coamings + drip trays sloped to dedicated NH_3 drain/KO tank (not general bilge), • Segregation & backflow control; Physically segregate any bilge system that could contain dissolved NH_3, blind cross-connections; overboard valves locked/removed in way of NH_3 drains. • Processing-first routing (vapour & liquid); Route tank/line vents, PRD discharges, purges and drain-tank vents to vapour-processing (scrubber/oxidizer/diffusion water tank) • Runoff management during firefighting/wash-down; If water fog/mist is used, treat runoff as contaminated; seal scuppers on alarm; collect to NH_3 drain/KO tank for processing.

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Detection & hard actions to cap inventory; Fixed NH_3 detection in ER; 25 ppm alarm and 50 ppm auto isolation • Ventilation & intake protection; ≥ 30 ACH extraction for fuel sub-enclosures with auto-boost on gas alarm; loss-of-vent ⇒ ESD. Fit intake sensors to close dampers/stop fans/recirc so vapour from drains/processing cannot be re-ingested. • Instrumentation of drains; pH/EC monitoring on drain/KO tanks; H/HH to CCR; sample ports for chemical analysis; hydrocarbon sheen alarm where co-fuels present (lube/fuel oil). • Cause & Effect (C&E); Gas ≥ 50 ppm or Fire ⇒ stop NH_3 pumps → profiled ESD closures (surge-safe) → enable local water-mist, seal scuppers, start drain-transfer to processing, close intakes, boost extraction; log times.
	Failure of inerting/purging of enclosures	• Define the enclosure/annulus performance target; (a) continuous extraction ~≥ 30 ACH through the annulus/box, or (b) N_2 purge/pressurization (IEC 60079-2) with an O_2 limit (project target, e.g., ≤ 8–10 vol %) and pressure/flow proving interlocked to operation • N_2 supply that can't quietly fail; Two independent N_2 sources (generator + bottle rack, or dual gensets) with auto-changeover, • Annulus/enclosure monitoring & trips; Combine O_2 analyzers (continuous) and NH_3 detectors (fast leak pickup) • Ventilation engineered for fuel sub-enclosures; Provide independent extraction ≥ 30 ACH; on NH_3 alarm auto-boost and (where practicable) divert exhaust to vapour-processing; treat loss-of-ventilation ⇒ ESD • Routing to a safe place (processing-first); Normal annulus/box exhaust and purges go to vapour-processing (scrubber/oxidizer/diffusion water tank); reserve mast for emergency with dispersion/no-re-ingestion evidence for intakes. • ESD sequencing (surge-safe); Cause & Effect: 25 ppm → alarm & vent boost; 50 ppm or O_2-High/N_2-Low → pump stop → profiled ESD-valve closure • Purge/pressurization of local cabinets; Apply IEC 60079-2 to analyzer/valve cabinets: purge timing, pressure proving, auto-shut on loss of pressurization; interlock "Cabinet Purge OK" to ammonia operation. • Ops & ship–shore integration; Use ISO 20519-style checklists and ship/shore ESD link (SSL) so enclosure/annulus trips stop both sides during transfers/commissioning.

Table 3: Hydrogen safety function requirements

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
Bunker station + Transfer to storage tank	CH_2 - Rapid dispersion of Compressed Hydrogen (CH_2) following a leak or release	• Gas Detection • ESD & Isolation • Ventilation / Dispersal Design • Hazardous Area Classification (HAC) • Ignition Source Control • Pre-bunkering Integrity Checks
	CH_2 - High-Pressure Release During Bunkering (accidental disconnection, hose rupture)	• High-integrity breakaway couplings • Automatic Emergency Shutdown (ESD) system • Excess flow check valves • Pre-cool/pre-pressure equalization logic
	CH_2 - Jet fire risk	• Gas Detection & ESD Isolation • Breakaway Couplings & Hose Management • Jet Fire Detection & Isolation • Physical Barriers & Separation Distances • Emergency Venting & Blowdown Systems • Crew Protection Measures • Passive Fire Protection (PFP)
	CH_2 - Jet Fire or Hydrogen Ignition Near Manifold	• Local gas detection and thermal detection • Fire detection and deluge (if enclosed) • Hot surface zoning and Ex-proof electrical equipment • Rapid isolation via remotely operated shut-off valves
	CH_2 - Permeation or micro-leakage during and after transfer	• Use of certified hydrogen-compatible materials • Double-walled pipes or enclosure of transfer line • Continuous leak detection inside enclosures • Pressure decay tests or vacuum interstitial monitoring
	CH_2 - Venting or blowdown during emergency shutdown	• Controlled vent stacks directed away from personnel zones • Gas dispersion modeling (CFD or equivalent) • Interlocks preventing venting near ignition sources • Time-delayed staged depressurization logic
	CH_2 - Inadequate Emergency Shutdown (ESD) Logic and Human Factors	• Integrated ESD buttons at manifold and control room • Clear operator visibility and signage • Interface interlock between ship and shore • Alarm escalation hierarchy
	LH_2 - Cryogenic embrittlement	• Material Selection & Qualification (Cryo-rated materials) • Temperature Monitoring • Redundant Isolation & ESD Valves • Inspection & Maintenance • Pressure Relief Devices (PRDs) • Breakaway Couplings
	LH_2 - Cryogenic Leak or Spray from Transfer Line or Coupling	• Double-walled vacuum-insulated piping • Drip trays and cryo spill barriers • Quick-closing ESD valves • Temperature and pressure interlocks
	LH_2 - Uncontrolled Boil-Off During Transfer (heat ingress)	• Pre-cooled fill lines and hoses • Boil-off gas (BOG) return or reliquefaction • Insulated bunkering interfaces • Flow metering and heat flux monitoring
	LH_2 - Hydrogen Accumulation Due to Leakage or Purging	• Continuous gas detection (cryogenic- compatible) • Forced mechanical ventilation • Leak-proof hose connections with purge interlocks

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Pre- and post-bunkering inert gas purging
	LH_2 - Fire/Explosion from Ignition of LH_2 Vapor Cloud	• Hazardous area classification and zoning • Ex-proof equipment (IECEx/ATEX certified) • Immediate ESD logic tied to detection • Controlled vent mast for purged gases
	LH_2 - Ice Blockage or Overpressure in Hose/Manifold	• Pressure and temperature interlocks • Thermal conditioning of hose and manifold • Blowdown valve to evacuate residual liquid • Real-time blockage detection with alarm
Storage Tank + Tank Connection Space (TCS) + Transfer Pipes to FPR	CH_2 - High-Pressure Gas Leakage	• Pressure-rated components • Leak detection (fixed sensors) • Automatic isolation (ESD valves)
	CH_2 - Embrittlement of Storage Systems	• Material compatibility and permeation resistance • Structural intergrity assurance • Temperature and Pressure Management • Inspection and monitoring provisions
	CH_2 - High-pressure PRD discharge, high buoyancy, low ignition energy, jet fire potential, jet flame length, higher flame speed, Jet fire potential, high-pressure PRD discharge	• Leak and Pressure Monitoring • Flame Arrestors / Deflectors • Ventilation & Dilution • Controlled Venting • Hazard Zone Control • Computational Validation (CFD)
	CH_2 - High-Pressure Release or Leakage in Tank Connection Space	• Gas-tight enclosure of tank connection space • Gas Detection (low ppm sensitivity) • Ventilation (continuous and fail-safe) • ESD & Isolation (quick-close valves at tank penetrations) • Venting/Blowdown (controlled to safe mast locations) • Ignition Source Control (Ex-rated equipment, hot surface limits) • Structural Fire Protection (PFP) for TCS boundaries
	CH_2 - Overpressure or Blowout in Storage Tank (COPV)	• Burst disc or pressure relief devices (PRDs) rated for COPVs (thermal & pressure-activated) • Redundant Tank pressure monitoring and interlock shutdown logic • Structural integrity of tank supports during relief • Vent stack to disperse released hydrogen safely and CFD-validated clearance • Fire protection (deluge/PFP to limit tank heating) • Material qualification for cyclic fatigue and impact resistance
	CH_2 - Material Degradation or Leakage Over Time (Hydrogen Embrittlement)	• Use of Type III/IV COPVs with certified liners • Protective coatings and barrier films for hydrogen permeation • Periodic NDE inspection or health monitoring of tank shell • Materials tested for embrittlement and permeability • Leak Detection (ultra-low ppm sensors and vacuum interstitial monitoring for double-wall systems). • Pressure Cycle Monitoring • Redundant Isolation Valves & PRDs
	LH_2 - Tank Insulation and Boil-off Management; Loss of containment due to insulation failure →Excessive boil-off → pressure rise or vent release → Fire or explosion due to accumulated hydrogen	• Vacuum insulation or multi-layer insulation • Boil-off gas (BOG) recovery or controlled venting • Tank pressure monitoring and relief • Passive fire protection
	LH_2 - Storage; Tank Connection Space Gas Detection and Ventilation Hydrogen accumulation in semi-enclosed space;	• Continuous gas detection (cryogenic hydrogen compatible) • Forced mechanical ventilation • Automatic Emergency Shutdown (ESD) linkage • Gas-tight bulkhead design and ATEX zoning

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
	Delayed detection → explosion risk Inadequate ventilation → flammable mixture	
	LH_2 - Cryogenic Hydrogen Leak in Tank Connection Space	• Continuous hydrogen gas detection (cryogenic-compatible) • Forced mechanical ventilation of tank connection space • Gas-tight separation from adjacent spaces • Automatic ESD (Emergency Shutdown) interlock with detection • Vent/Blowdown Systems • Ignition Source Control • Structural Fire and Thermal Protection
	LH_2 - Overpressure or Structural Damage from Boil-Off or Heat Ingress	• Vacuum-insulated tank with multilayer insulation (continuous vacuum monitoring and alarm) • Pressure relief valves (PRVs) for tank and piping • Redundant Tank Pressure & Temperature Monitoring • Emergency vent mast to safe location • BOG Management System • Passive Fire Protection (PFP) or Deluge
	LH_2 - Ice Accumulation or Cold Damage Around Tank Interface	• Drainage and de-icing systems • Freeze-protected structural elements • Temperature and moisture monitoring at critical joints • Heated Purge or Heat Tracing • Insulation & Vacuum Jacket Integrity • Redundant Valve and Sensor Design
Fuel Preparation room + Transfer to engine room	CH_2 - High-Pressure Release in Fuel Preparation Room	• Gas-tight enclosure with controlled ventilation • High-speed CH_2 gas detection system • ESD valves upstream and downstream of the preparation unit • Overpressure protection and relief routing • Ignition Source Control • Passive Fire Protection (PFP)
	CH_2 - Inadequate Pressure Regulation or Malfunction	• Redundant pressure regulation system with failsafe venting • Pressure and Temperature Monitoring • Thermal conditioning (if needed) to avoid low-temp lockout • Relief Devices and Blowdown Systems • Emergency Shutdown (ESD) Valves • Periodic Functional Testing and Diagnostics
	CH_2 - Hydrogen Migration to Adjacent Spaces via Piping Leaks	• Double-walled piping or ventilation ducts around single-wall pipes • Gas/ Leak detection within pipe trays and adjacent spaces • Zoning classification of passageways or corridors • Isolation valves between spaces • Ventilation & Purge Systems • Bulkhead & Deck Sealing
	CH_2 - Explosion in enclosed space	• Gas Detection & Alarm Systems • Ventilation & Purging • Emergency Shutdown (ESD) & Isolation • Explosion Venting & Overpressure Protection • Ignition Source Control • Double-Wall or Ducted Piping
	LH_2 - Cryogenic Hydrogen Leak or Pooling in Enclosed Prep Room	• Continuous hydrogen detection (cryo-calibrated) • Forced ventilation (positive air exchange) • Cryogenic Spill Containment & Drainage • Emergency Shutdown (ESD) valve integration with sensors • Insulation & Vacuum Integrity Monitoring • Freeze Protection

Fuel Handling Zone	Safety consideration	Safety function requirements / Risk reduction measures
		• Ignition Source Control • CFD-Optimized Design • Passive Fire Protection (PFP)
	LH_2 - Boil-off Gas (BOG) Accumulation or Overpressure in Piping	• Insulated piping with boil-off tolerance • Pressure Relief Devices (PRDs) and flow restrictors • BOG Management Systems • Pressure and temperature interlock with engine inlet • Dual-Level Gas Detection in FPR & Ducts • Ventilation (Dual-Level and Fail-Safe)
	LH_2 – Icing or Blockage in Fuel Lines, Engine Interface & All Cryogenic Fuel Handling Equipment in the FPR	• Temperature & Moisture Monitoring • Heat Tracing & Purge Systems • Vacuum Jacket & Cold Spot Monitoring • Emergency Shutdown (ESD) Valves • Pressure Relief Devices (PRDs) • Redundant Flow Paths & Components • Periodic De-Icing & Accessible Drainage
	LH_2 – Malfunction of Vaporizers or Final Fuel Conditioning Units & Equipment in the Fuel Preparation Room (FPR)	• Redundant Vaporizers & Conditioning Units • Diagnostics & Continuous Monitoring • Freeze Protection & Purge Systems • Pressure Relief Devices (PRDs) • Emergency Shutdown (ESD) & Isolation • Gas Detection & Ventilation
	LH_2 - Cold burns / phase explosion	• Leak Detection & Isolation (ESD) • Spill & Spray Containment • Pressure Relief Devices (PRDs) • Insulation & Shielding • Crew Protection & Access Control • Ventilation (Dual-Level) • Emergency Drainage / Evacuation of Pools
Engine room	Hydrogen Leak and Accumulation	• Gas Detection • Ventilation • ESD & Isolation
	Fire or Explosion (Ignition of Accumulated Gas)	• Ignition Source Control • Flame Detection • ESD & Isolation • Fire Suppression
	Ventilation Failure	• Ventilation Monitoring • Interlock with ESD • Gas Detection Redundancy
	Gas Detection Failure or Insufficient Coverage	• Redundant Detection (2oo3 voting) • CFD-Optimized Placement • Routine Calibration & Diagnostics
	Inadequate Emergency Shutdown (ESD) Logic	• Sequenced Isolation & Blowdown • Sensor Voting Logic • Fail-Safe Defaults
	Hot Surfaces / Ignition Sources	• Ex-Rated Equipment • Hot Surface Temperature Limits • Physical Separation
	Human Factors	•Alarm Prioritization & HMI Design • ESD Switch Ergonomics • Crew Training & Drills