A Failure Mode Taxonomy for Reciprocating Liquid Hydrogen Pumps

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Abstract: The transition toward hydrogen-powered transportation requires fueling systems capable of sustaining high-availability operation under demanding thermal and pressure conditions. Reciprocating liquid hydrogen pumps are one of the most critical systems within hydrogen refueling stations. They enable the pressurization and transfer of liquid hydrogen during fueling operations. However, the extreme operating environment within liquid hydrogen fueling hardware introduces failure behaviors that must be understood further. Reliability issues in pumps are reported as system failures such as abnormal high vapor return, failure to operate, or external hydrogen leakage, but these observable outcomes do not directly reveal the internal component failure that causes the pump's failure behavior. We present a structured failure mode taxonomy for reciprocating liquid hydrogen pumps. The framework categorizes observable failure modes from contributing subsystem and component failure modes and organizes their relationships within clearly defined system boundaries. By formalizing this taxonomy, we provide a framework that supports more consistent failure classification, improved diagnostic reasoning, and clearer alignment between operational reporting and reliability engineering analysis. This structured approach provides a foundation for future failure mechanism focused studies, reliability model development, and reliability improvement efforts in liquid hydrogen pump systems.

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1. INTRODUCTION

The expansion of hydrogen fueling infrastructure has increased the need for reliable and safe station operation. While hydrogen fueling stations have demonstrated the ability to meet throughput requirements, operational reliability continues to trail behind that of mature energy infrastructure [1, 2]. A substantial portion of station downtime is associated with failures of equipment interfacing with critical hydrogen systems including dispensers, compressors, and valves. This leads to reduced availability, increased maintenance costs, and, in some cases, safety-relevant events involving abnormal operating conditions or unintended hydrogen releases [2].

Reciprocating liquid hydrogen pumps play a central role in station operation but also represent a critical system whose failure can disproportionately disrupt fueling performance [3]. High-capacity hydrogen fueling stations use reciprocating liquid hydrogen pumps because they can generate the high discharge pressures required for hydrogen dispensing while maintaining controllable mass flow and high storage density. Despite the importance of the pump, there is little published data about their failure causes. Comparatively limited effort has been devoted to systematically linking observed high-level pump failures to the combination of potential root cause lower-level component failures. This disconnect complicates consistent root-cause analysis following pump failures, limits the ability to translate failure data into targeted reliability and component improvements, and contributes to unscheduled maintenance that increases station downtime and missed fueling events.

Reciprocating liquid hydrogen pumps are particularly prone to reliability challenges because the extreme service conditions, including temperatures near 20 K, large pressure gradients, operating pressures up to 90 MPa, cyclic mechanical loading, and continuous exposure to concentrated hydrogen [4]. These conditions give rise to degradation processes that are uncommon in conventional pumping applications and that evolve differently under cryogenic hydrogen service [5]. There are also limitations with the ability to test the equipment in hydrogen environments [4]. As a result, failures occur more frequently in the pumps and internal components, and these failures can manifest as a variety of failures that lead to extended station downtime and maintenance.

Research has begun to address reliability considerations for reciprocating liquid hydrogen pumps, including analyses that identify commonly observed failure modes [4, 6]. Pumps used in fueling stations encompass a wide range of technologies, including motors, belts, valves, seals, filters, and associated interfaces, each of which can fail in a variety of ways and affect the pump differently. However, the pump failure modes are introduced without consideration of the specific subsystem or component failure modes that produce them. As a result, existing frameworks provide limited guidance for future reciprocating pump studies and improvements including post-mortem analysis, accelerated life cycle testing, FMEA development, forensic inspection, or predictive reliability modeling.

Reliability studies in hydrogen systems have demonstrated the value of explicitly linking observable failure modes to underlying component failure modes through structured analytical frameworks [7-13]. Such approaches improve interpretability, enable consistent failure classification, and support quantitative modeling, even in data-limited environments [7-13]. However, subsystem and component linked frameworks have not yet been developed for reciprocating liquid hydrogen pumps.

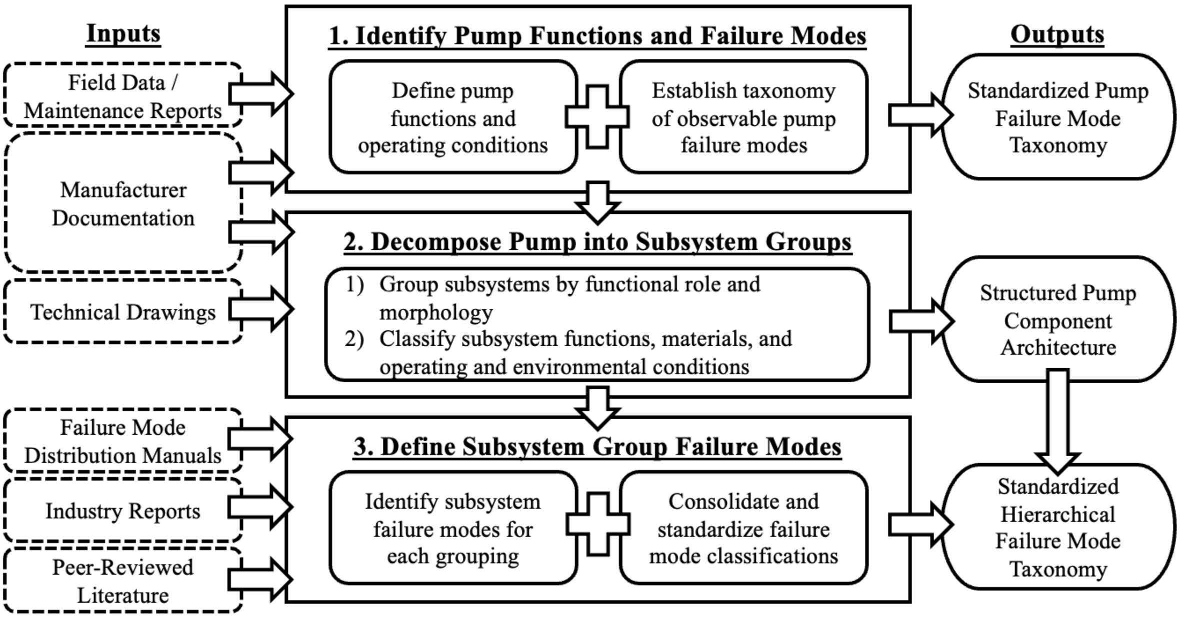
In this paper, we establish a structured failure mode taxonomy for reciprocating liquid hydrogen pumps through the analysis and synthesis of peer-reviewed literature, industry reports, maintenance observations, and manufacturer documentation related to cryogenic hydrogen pumping systems. We analyzed the information to identify system, subsystem, and component failures that are prevalent under liquid hydrogen service conditions. The resulting framework provides a consistent basis for organizing and classifying failure modes across the pump system to supporting future reliability studies, FMEA development, Bayesian casual modeling, post-mortem analysis and failure mechanism investigations for cryogenic hydrogen equipment.

2. APPROACH AND METHODS

We employ a structured, multi-source analysis methodology, outlined in Figure 1, to develop a standardized failure mode taxonomy for reciprocating liquid hydrogen pumps. The inputs to the framework consist of field and literature information sources, including maintenance records and operational failure descriptions reported in prior studies [4], manufacturer technical documentation describing component architecture and operating conditions [14-16], technical drawings and component descriptions defining physical system boundaries [14], failure mode distribution manuals [17, 18], reports documenting hydrogen fueling station reliability trends [1, 4], and peer-reviewed literature detailing failures under cryogenic hydrogen service [19-29]. We systematically combined these diverse inputs to capture both operationally observable failure behavior and component failure mode evidence. The integration of these sources ensures that the resulting taxonomy reflects real-world pump configurations and is grounded in documented performance trends, field observations, and established reliability classifications.

Using this data, we then followed a three-step process to obtain the taxonomy. First, the system boundary and primary pump functions were defined to establish which components, interfaces, and operational behaviors were included within the scope of the analysis. This step also identified functional roles of the pump so that failures could later be classified according to deviations from those intended functions. Second, the pump was decomposed into a subsystem architecture consisting of the motor, belt drive, warm end crank drive, and cold end assembly, with the cold end further decomposed into component elements due to its elevated failure rate. Third, failure information extracted from literature, maintenance observations, manufacturer documentation, and reliability databases was reviewed and harmonized into standardized terminology by grouping similar operation symptoms, degradation behaviors, and functional losses into consistent failure mode classifications. The output of this process is a set of standardized taxonomies: one for pump failure modes, and several subsystem and component failure mode taxonomies corresponding structured pump component architecture also developed in this work.

Figure 1: Analysis methodology for failure mode taxonomy creation



This structured process of system boundary definition, functional decomposition, and terminology harmonization allowed us to produce three intermediate outputs: a functionally anchored pump system failure mode taxonomy, a subsystem- and cold end component-based architecture, and a failure mode classification framework suitable for consistent cross-subsystem and cross-component comparison.

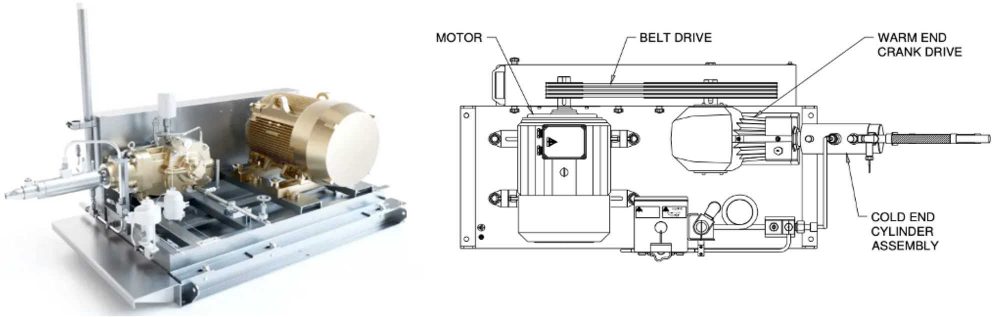
3. PUMP, SUBSYSTEM, AND COMPONENT FUNCTIONS AND DESCRIPTIONS

3.1. Pump Functions and System Boundaries

The reciprocating liquid hydrogen pump system is designed to transfer liquid hydrogen from low-pressure storage conditions to the high-pressure conditions required for vehicle fueling and industrial hydrogen delivery applications. During operation, the pump intakes cryogenic liquid hydrogen through the suction inlet, pressurizes the fluid within the cold end assembly, and discharges the hydrogen at elevated pressures for downstream storage or dispensing [14].

The system boundary for this work includes the primary mechanical and fluid-handling components directly associated with the reciprocating pump assembly, specifically the motor, belt drive, warm end crank drive, and cold end assembly, outlined in Figure 2. Auxiliary infrastructure components external to the pump assembly, such as upstream storage tanks, external piping networks, heat exchangers, control systems, downstream dispensing equipment, and gaseous hydrogen return lines are excluded from this work and considered outside of the system boundary.

Figure 2: (Left) Reciprocating cryogenic pump by Nikkiso [15]. (Right): Labeled top-down view of a reciprocating cryogenic pump [14].



3.2. Subsystem Descriptions and Functions

The pump assembly is divided into four primary subsystems: the motor, belt drive, warm end crank drive, and cold end assembly. Each subsystem performs a distinct mechanical or thermodynamic function that collectively enables the continuous delivery of high-pressure liquid hydrogen for fueling applications.

The motor is the primary energy source for the reciprocating pump system and is responsible for supplying the rotational energy required to drive the entire pumping process [14]. During operation, the motor provides continuous torque to the mechanical transmission system while maintaining stable rotational speed under varying loading conditions. Because the pump assembly operates in industrial and hazardous environments, the motor system must comply with electrical safety requirements and maintain reliable operation under prolonged duty cycles [14].

The belt drive transfers rotational power from the motor to the warm end crank drive mechanism while providing flexibility in shaft alignment and rotational speed transfer. This subsystem commonly consists of pulleys, belts, and supporting rotating hardware that mechanically couple the motor output shaft to the warm end crank drive assembly. The belt drive also helps reduce the direct transmission of shock loading and vibration between the motor and the warm end crack drive subsystems [14].

The warm end crank drive converts the rotational motion supplied through the belt drive into the reciprocating linear motion required for piston compression within the cold end assembly. This subsystem typically comprises components including crankshaft, connecting rods, crossheads, bearings, and associated mechanical linkage components that coordinate the cyclic piston movement. The warm end operates near ambient temperature and functions as the mechanical transition region between the external drive system and the cryogenic compression chamber inside the cold end assembly [14]. One of its most important functions is maintaining thermal isolation between the ambient mechanical hardware and the cryogenic cold end subsystem exposed to liquid hydrogen [14]. The reciprocating mechanism must therefore sustain large cyclic stresses while minimizing heat transfer into the cold end.

The cold end assembly contains the primary cryogenic compression chamber and directly interfaces with liquid hydrogen during the pump's operation. This subsystem performs the suction, compression, and discharge functions necessary to pressurize cryogenic hydrogen to fueling pressures [14]. The cold end generally includes the discharge valve, housing and vacuum jacket, low pressure and interfacing seals, piston rod, piston guide rings, suction filter, and suction valve. Because it is in direct contact with cryogenic hydrogen, the cold end operates under severe thermal and hydrogen exposure conditions, including cryogenic temperatures, high-pressure cycling, rapid fluid acceleration, and repeated mechanical loading, highlighting the unique environmental demands imposed on the cold end.

3.3. Cold End Assembly Descriptions and Functions

The cold end assembly can be decomposed into a set of components, shown in Figure 3, that collectively enable liquid hydrogen compression and containment. These components perform distinct mechanical, hydraulic, and sealing functions, and degradation within any of them may lead to observable higher-level cold end failure modes. Table 6 summarizes the primary cold end components, their descriptions, and their intended functions, based on manufacturer documentation and prior cold end reliability analyses.

Figure 3: (Left) Reciprocating cryogenic pump from Indian Compressors Ltd [16] with the cold end circled in red. (Right): Labeled internal view of the cold end's components [14].

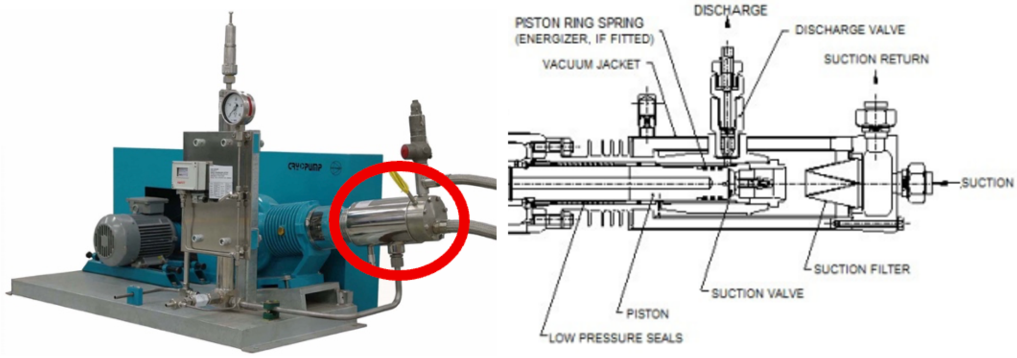


Table 6: Components within a cold end assembly

Component	Description	Function
Discharge Valve	Side-mounted poppet valve positioned slightly beyond the end of the piston stroke. High nickel/copper alloy or stainless steel body with beryllium copper spring	Discharges liquid out of the pumping chamber when the cylinder pressure exceeds downstream pressure and reseats during suction to prevent backflow
Housing and Vacuum Jacket	Stainless steel housing that contains the piston/rod, suction and discharge valves, and suction filter. Incorporates a vacuum jacket surrounding the piston	Provides pressure containment for the cold end and structure for internal components. Minimizes heat transfer from the ambient environment into the cryogenic pumping chamber
Low Pressure Seals, Interfacing Seals, and Piston Guide Rings	PTFE based material with 15% glass fill for low pressure seals and 60% bronze fillings for guide rings placed around the piston / rod interfacing between the cold end and the warm end	Prevent leakage of liquid into the atmosphere or surrounding components, mitigate heat ingress, and promote piston alignment
Piston	Rod that is driven from the warm-end crosshead and equipped with multiple rings that seal the pumping chamber from the rest of the housing	Reciprocate to draw liquid in on the suction stroke and pressurize and discharge the liquid on the pumping stroke
Suction Filter	Fine-mesh (~150 µm / 100-mesh) incorporated within the pump suction chamber	Prevents debris/ice from entering and damaging the cold end and downstream components
Suction Valve	One-way flat plate type check valve located at the cold end cylinder head.	Admits liquid into the pumping chamber on the suction stroke and then closes to trap liquid for pressurization during the discharge stroke

4. FAILURE MODE IDENTIFICATION

A failure mode is defined as *the manner or way in which a system, subsystem, component fails to perform its intended function under operating conditions* [30]. The following section presents the failure mode taxonomies developed for the reciprocating liquid hydrogen pump at the pump, subsystem, and cold end component levels. These taxonomies provide a standardized framework for classifying function failures and relating lower-level degradation to higher-level operational pump failures.

4.1. Pump Failure Modes

Reising identified and defined seven pump failure modes that capture the functional failures of reciprocating liquid hydrogen pumps during operation [4]. She used historical maintenance records and field observations from hydrogen fueling stations. Manufacturer documentation indicates that many failures are preceded by changes in operating behavior, including elevated vapor return rates, unstable pressure build-up during compression, or abnormal vibration and acoustic signatures [14]. These behaviors are treated as indicators of internal degradation rather than root causes and often occur before a complete loss of pump functionality. The taxonomy, summarized in Table 1, is adopted in the present study to define the top-level failure modes of the pump and to provide consistent terminology for subsequent analysis. These pump failure modes encompass both performance-related degradation and loss of mechanical or containment integrity.

Table 1: Failure mode taxonomy of a cryogenic hydrogen pump [adapted from 4]

Failure Mode	Description
Abnormal High Vapor Return	Producing excessive hydrogen vapor leading to increased vapor return to LH_2 storage tank
Abnormal Low Output	Unable to reach the demanded output mass flow/pressures
Damaged	Has visible mechanical damage
External Hydrogen Leak	Hydrogen is released from the pump to the external environment
Fail to Operate	Pump unable to build any pressure, move product and/or operate on demand
Internal Hydrogen Leak	Hydrogen is released within the inside of the pump system
Noise	Pump is producing an abnormal or excessive audible noise during operation

4.2. Motor Subsystem Failure Modes

The motor failure modes summarized in Table 2 represent functional deviations that prevent the motor from reliably supplying the rotational speed and torque required to drive the pump system. Because the motor serves as the primary power source for the pump, its failure modes are primarily associated with loss of motion control, inability to respond correctly to electrical commands, or unstable rotational output. Several of these failure modes, including abnormal instrument reading, erratic output, abnormal high output, and abnormal low output, are directly related to the motor's inability to correctly interpret or execute commanded electrical control signals, resulting in rotational behavior that deviates from the intended operating condition. In contrast, failure modes such as fail to start on demand, fail to stop on demand, and spurious stop represent losses of operational controllability that can interrupt or prevent hydrogen compression entirely. The remaining failure modes, including overheating, vibration, noise, and damage, are treated as observable indicators of abnormal internal electrical or mechanical behavior that may precede complete motor failure or propagate downstream into higher-level pump operational failures. Because the motor governs the rotational speed and torque supplied to the belt drive and warm end crank drive, Hamani et al. [20] noted that motor faults can produce degraded operational performance and abnormalities that may ultimately manifest as higher-level pump failure modes, including abnormal low output, failure to operate, or noise during pump operation.

Table 2: Failure mode taxonomy of a cryogenic hydrogen pump's motor

Failure Mode	Description
Abnormal Instrument Reading	Incorrectly responding to commanded electrical control signals
Damaged	Has visible mechanical damage
Erratic Output	Inconsistent projection of demanded rotational velocity or torque
Fail to Start on Demand	Unable to initiate rotation when commanded
Fail to Stop on Demand	Unable to cease rotation when commanded
Abnormal High Output	Output exceeds demanded rotational velocity or torque
Abnormal Low Output	Unable to reach the demanded output rotational velocity or torque
Noise	Producing an abnormal audible noise
Overheating	Generating excessive heat above thermal limits during operation
Spurious Stop	Unexpectedly ceasing operation during operation
Vibration	Producing abnormal and excessive mechanical vibration during operation

4.3. Belt Drive Subsystem Failure Modes

The belt drive failure modes summarized in Table 3 represent failures that impair the system's ability to reliably transmit rotational motion and torque from the motor to the warm end crank drive. These failures are primarily associated with loss of mechanical integrity, unstable engagement between rotating components, or improper geometric alignment within the drive system. Because the belt drive serves as the mechanical interface between the motor and the warm end crank drive, degradation within this subsystem can disrupt stable power transmission, reduce rotational efficiency, and introduce abnormal dynamic loading into downstream pump subsystems. Chu et al. [21] noted that vibration-related faults in rotating machinery systems, including belt-related damage, misalignment, and slipping, can progressively degrade machine performance and contribute to premature operational failure. These effects can ultimately manifest as higher-level pump failure modes including noise, abnormal low output, or complete failure to operate during service.

Table 3: Failure mode taxonomy of a cryogenic hydrogen pump's belt drive

Failure Mode	Description
Damaged	Has visible mechanical damage
Misaligned	Belt, pulley, and or shafts are in a nonstandard orientation or position
Slipping	Failing to maintain consistent engagement between components
Vibration	Producing abnormal and excessive mechanical vibration during operation

4.4. Warm End Crank Drive Subsystem Failure Modes

The warm end crank drive is responsible for sustaining controlled reciprocating motion between the external drive system and the cold end assembly. Consequently, the failure modes identified in Table 4 are centered on disruptions to motion conversion, force transmission, thermal isolation, and dynamic mechanical stability during cyclic operation. Dong et al. [22] noted that cyclic torsional and bending loading within reciprocating plunger pump crank systems can accelerate subsystem degradation and contribute to broader system-level failures. Instability within the warm end crank drive can disrupt reciprocating compression behavior, alter piston motion, and change sealing between the warm end and the cold end assembly. These effects may propagate upward into observable pump system operational failures including abnormal low output, failure to operate, abnormal high vapor return, internal and external hydrogen leaks, or noise.

Table 4: Failure mode taxonomy of a cryogenic hydrogen pump's warm end crank drive

Failure Mode	Description
Damaged	Has visible mechanical damage
Erratic Output	Inconsistent projection of demanded force
Fail to Operate	Unable to project any force
Abnormal High Output	Output exceeds demanded translation velocity or force
Abnormal Low Output	Unable to reach the demanded output translational velocity or force
Noise	Producing an abnormal audible noise
Overheating	Generating excessive heat above thermal limits during operation
Spurious Stop	Unexpectedly ceasing operation during operation
Thermal Isolation Loss	Unable to prevent heat transfer into the cold end assembly
Vibration	Producing abnormal and excessive mechanical vibration during operation

4.5. Cold End Subsystem Failure Modes

The cold end assembly is the only subsystem within the cryogenic pump that directly interfaces with liquid hydrogen during suction, compression, and discharge operations. Consequently, the failure modes summarized in Table 5 are associated with the loss of hydrogen containment, thermal stability, compression capability, or stable cryogenic fluid handling within the cold end assembly. Historical maintenance records and operational observations analyzed by Reising [4] showed that corrective actions associated with observable pump operational failures consistently involved maintenance, repair, or replacement of cold end hardware rather than intervention on the motor, belt drive, or warm end crank drive. This repeated reliance on cold end corrective actions indicates that the degradation responsible for many observable pump symptoms primarily originated within the cold end assembly. Accordingly, the pump operational failure modes identified by Reising [4] are also adopted in the present work as representative failure modes of the cold end assembly.

Table 5: Failure mode taxonomy of a cryogenic hydrogen pump's cold end assembly

Failure Mode	Description
Abnormal High Vapor Return	Producing an excessive vapor return to LH_2 tank
Abnormal Low Output	Unable to reach the demanded output mass flow/pressures
Damaged	Has visible mechanical damage
External Hydrogen Leak	Leaking hydrogen into the environment
Fail to Operate	Unable to build any pressure, move product and/or operate on demand
Internal Hydrogen Leak	Hydrogen is leaking within the inside of the cold end or pump system
Noise	Producing an abnormal audible noise

4.5.1. Discharge and Suction Valves Failure Modes

The discharge and suction valves are critical flow control elements in the cold end. The majority of the failure modes in Table 7 are driven by an inability to open and close on demand, loss of stable valve motion control, or leakage through the valve seat. Reliable closure and reseating of these valves are essential because sealing is required to trap liquid around the piston, build compression pressure, and ultimately discharge hydrogen at the required pressure and mass flow [14]. If the discharge valve fails to open at the required time, the cold end cannot adequately output pressurized hydrogen, whereas premature opening or leakage can reduce effective discharge pressure and lower or stop delivered mass flow. Similarly, if the suction valve opens at the wrong time or leaks during compression, hydrogen can be forced to flow backward toward the supply tank, and if it closes too early or fails to open during suction, insufficient hydrogen enters the cold end, directly reducing achievable system mass flow or halting cold end operation. This interpretation is supported by Li et al. [23], who experimentally and numerically showed that improper opening and closing dynamics of suction and discharge valves in a reciprocating piston pump directly disrupt pressure build-up and flow control, with valve timing errors, unstable motion, and seat impact behavior identified as primary drivers of degraded pump performance and valve-related faults.

Beyond direct flow-control loss, valve-related faults can also contribute to secondary cold end behaviors that further degrade performance and complicate diagnosis, particularly through coupled thermal and dynamic effects. Stops et al. [24] proved an external hydrogen leak can also increase local heat ingress by degrading insulation performance and exposing cryogenic surfaces to warmer surroundings, which accelerates liquid-to-vapor conversion in the cold end. This causes rapid pressurization and hydrogen release venting behavior. The heat-ingress pathway provided by this failure can increase vapor return generation and reduce or prevent stable liquid discharge through the discharge valve. Moreover, Chen et al. [25] saw unstable valve dynamics can also manifest as audible noise, since valve chatter produces flow-induced vibration and pressure fluctuations when the valve element motion becomes unstable.

Table 7: Failure mode taxonomy for the cold end's discharge and suction valves

Failure Mode	Description
Abnormal High Output	Exceeds the demanded output mass flow / pressures
Abnormal Low Output	Unable to reach the demanded output mass flow / pressures
Chatter	Loss of steady position, valve toggles rapidly in the absence of command
Damaged	Has visible mechanical damage
Erratic Output	Inconsistent output of hydrogen
External Hydrogen Leak	Leaking hydrogen into the environment
Fail to Close	Remains open when commanded to close

Fail to Open	Remains closed when commanded to open
Fail to Operate	Does not function on demand
Internal Hydrogen Leak	Hydrogen leakage within the valve assembly
Leakage in Closed Position	Leaking hydrogen internally and exclusively through the seat when commanded to close
Plugging	Buildup of material restricting flow out of valve
Spurious Operation	Activation without specified demand

4.5.2. Housing and Vacuum Jacket Failure Modes

The housing and vacuum jacket component provides the primary pressure boundary and thermal insulation required to maintain liquid hydrogen in a stable cryogenic state during compression [14]. The dominant failure modes for this component are summarized in Table 8 and include internal and external leakage, as well as reduced or lost thermal insulation. Because the cold end relies on both containment and thermal isolation to sustain liquid-phase operation, leakage or insulation degradation in this component can directly drive abnormal low output or a complete loss of output. If thermal insulation is reduced or lost, increased heat ingress can warm the hydrogen above its cryogenic liquid state, promoting boiling and vapor generation within the cold end [14]. The resulting two-phase behavior increases vapor volume and elevates local pressures, which can force hydrogen to be routed back toward the supply tank as vapor return rather than being discharged as pressurized liquid. This routing disrupts stable piston compression by reducing the effective liquid inventory available for pressurization and lowering the achievable liquid mass flow through the cold end, ultimately degrading the pump's ability to meet required system output. This relationship is supported by Kim et al. [26], who showed that cryogenic piston pump performance degrades when the working fluid experiences undesirable evaporation, and that increasing the subcooling degree reduces vapor generation and improves exhaust duty cycle and exhausted mass. This indicates that added heat input and reduced temperature control promote vapor formation that limits effective liquid discharge and increases return-type losses.

Table 8: Failure mode taxonomy for the cold end's housing and vacuum jacket

Failure Mode	Description
Damaged	Housing has visible mechanical damage
External Hydrogen Leak	Hydrogen leakage into the environment
Internal Hydrogen Leak	Hydrogen leakage within the cold end and vacuum jacket
Loss of Thermal Insulation	Absence of temperature insulation
Reduced Thermal Insulation	Unable to maintain required internal temperature

4.5.3. Low Pressure Seals, Interfacing Seals, and Piston Guide Rings Failure Modes

The low-pressure seals, interfacing seals, and piston guide rings have relatively few distinct failure modes outlined in Table 9, but they play an essential role in maintaining thermal integrity and ensuring stable piston guidance and alignment during operation [14]. These elements function as both sealing interfaces and mechanical alignment features, limiting heat ingress into the cold end while constraining piston motion to prevent lateral loading, uneven contact, and off-axis travel. If degradation, wear, rupture, or loss of sealing effectiveness occurs, increased heat ingress can promote abnormal vapor generation within the cold end, reducing the available liquid fraction and directly degrading achievable pressure build-up [24], [27]. Additionally, Deng et al. [28] showed that increased leakage through the piston clearance seals leads to a pressure drop during the discharge process and can prevent sufficient pressure build-up for reliable discharge. Deng et al. [28] indicates that guide-ring or sealing degradation that increases clearance and promotes misalignment-related leakage can directly reduce compression effectiveness and output stability. Finally, if a seal rupture or leakage occurs at these interfaces, hydrogen can leak past or out of the cold end boundary, creating both a direct loss of system performance and a potential external leak hazard depending on the leak path and operating conditions.

Table 9: Failure mode taxonomy for the cold end's low pressure seals, interfacing seals, and piston guide rings

Failure Mode	Description
Leak	Hydrogen leakage past seal interface
Misalignment	Seals and rings are in a nonstandard orientation or position
Rupture	Exhibits visible mechanical damage, fracture, and / or detachment from interface

4.5.4. Piston Failure Modes

The piston is the primary compression element in the cold end, and its reciprocating motion is essential for pressurizing hydrogen and driving flow through the suction and discharge valves to achieve the required system mass flow [14]. Accordingly, the piston failure modes summarized in Table 10, directly govern whether the cold end can sustain the cyclic pressure rise needed for discharge while maintaining stable intake during the suction stroke. However, piston misalignment can introduce unstable motion that accelerates wear or damage in adjacent cold end components, ultimately compounding degradation across the cold end and possibly generating noise. If the piston fails to operate correctly, the cold end cannot sustain adequate compression, which directly manifests as a complete failure to generate measurable hydrogen flow.

Table 10: Failure mode taxonomy for the cold end's piston

Failure Mode	Description
Damaged	Has visible mechanical damage
Fail to Operate	Unable to build pressure, move fluid, and / or operate on demand
Misalignment	Piston is in a nonstandard orientation or position

4.5.5. Suction Filter Failure Modes

The suction filter serves as the primary protective barrier preventing particulates from entering the cold end [14], and its dominant failure modes, shown in Table 11, fall into two main categories: flow restriction and loss of filtration integrity. Panda et al. [29] showed restriction-based failure modes can overly limit inlet flow into the pumping chamber, which reduces the available suction capacity and can initiate recirculation, ultimately degrading pump performance and contributing to abnormal low output or total loss of effective compression when the inlet restriction becomes severe. In contrast, filtration-integrity failures include bypass of unfiltered fluid or passage of oversized debris through the filter mesh, which can introduce contaminants into the cold end and drive downstream damage to valves, seals, and other interfaces. Because this debris passage occurs internally within the cold end boundary and compromises the intended clean-flow pathway, it is treated as an internal leak condition within the system, where unfiltered hydrogen and entrained debris are effectively leaking past the filtration barrier into protected regions of the cold end.

Table 11: Failure mode taxonomy for the cold end's suction filter

Failure Mode	Description
Bypass of Unfiltered Fluid	Fluid passes around filter
Damaged	Filter has visible mechanical damage
Passage of Oversized Particles	Particles above specified size pass through filter
Plugging	Buildup of material restricting output mass flow / pressures
Spurious Flow	Unstable of fluctuating mass flow / pressures
Restricted Flow	Restricts or completely prevents mass flow / pressures across filter

5. CONCLUSION

We developed a structured failure mode taxonomy for reciprocating cryogenic hydrogen pumps used in hydrogen fueling applications and established a framework for observable pump system, subsystem, and cold end-specific component failure modes. By defining consistent terminology and explicitly decomposing the pump into functional component groups, we provide a structured basis for interpreting operational failure behavior and collecting reliability data for reciprocating liquid hydrogen pump systems.

This taxonomy can support both reliability data collection and model development, including future failure mechanism mapping and hierarchical linkages to higher-level failures. The structured relationships developed in this work create a foundation for connecting physical degradation mechanisms occurring at the material level to component failure modes, subsystem failure modes, and ultimately system operational reliability modeling of pumps at hydrogen fueling stations.

Establishing linked hierarchal relationships will enable failure propagation pathways to be traced across multiple system levels, allowing observable operational symptoms to be associated with likely internal degradation processes. Such frameworks will improve forensic evaluation of failed pump hardware by allowing observed physical damage to be systematically and quantitatively linked back to operational symptoms and degradation histories. In addition, these relationships can support targeted reliability improvements, including redesign strategies and maintenance practice optimization, by identifying the specific components and interfaces most responsible for recurring operational failures.

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