

# A Systematic Literature Review on Risk and Reliability Analysis of Cryogenic Pumps

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**Abstract:** Cryogenic pumps play an important role in hydrogen fueling, transportation, and storage. The performance and reliability of a cryogenic pump directly affect the functionality of the entire hydrogen fueling station. The cryogenic pumping industry is slowly recognizing the need to optimize their pumps for the hydrogen pumping scenario. To this end, it is important to develop a more mechanistic understanding of the various failure behaviors and mechanisms as well as ways to predict when these events will occur. We conducted a systematic analysis of available scholarly sources to identify any failure and reliability models for a cryopump, as well as the reliability and risk studies methods performed. In this paper, we aim to (1) evaluate the available research on the risk, reliability, and safety of cryogenic pumps in various fields of engineering, (2) identify gaps in the studies, and (3) provide a basis for the development of higher reliability cryogenic pumps.

Key findings from the study highlight a limited exploration of the reliability and safety aspects of cryogenic pumps and a lack of unity in the language and definition of terms. We drafted a list of documented failure modes and mechanisms to create clearer terminology. These terms can be used to enable data collection and maintenance logging which in turn can inform reliability and risk analysis methodologies. By prioritizing reliability and safety in using cryogenic pumps, safer and more reliable technology can be ensured for emerging hydrogen fueling.

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## 1. INTRODUCTION

In recent years, research on complex engineering systems, particularly focusing on cryogenic pumps, has witnessed increased attention within scientific and engineering communities. Efficient and reliable cryogenic technologies have been receiving a growing demand in various industries such as aerospace, energy, and healthcare, therefore, research to explore novel designs, materials, and operational strategies to enhance pump reliability, performance, durability, and safety has found greater importance [1-3]. There are multiple categorizations for pumps based on their design and performance metrics and have been commonly investigated and discussed in the literature [4]. Cryogenic pumps have many applications in different fields of engineering and technology. Some of the major areas include fusion energy, aerospace engineering, cryogenic fluid technology, fuel systems (including production, transportation, storage, and distribution), and plasma physics [5-9]. These industries use diverse types of cryopumps as integral components of their system designs.

Cryogenic pumps can be categorized under vacuum pumps functioning at temperatures below 120 K (-243.4°F / -153°C) and pressures below 10<sup>-3</sup> Pa. They can be classified as entrapment or capture vacuum pumps, and reciprocating pumps, effectively trapping gas molecules through chemical or physical interaction within their cryogenically cooled internal surfaces. These pumps typically consist of five primary components: motor, belt drive assembly, warm end, intermediate, and cold end [4].

Existing research has largely concentrated on various aspects of systems incorporating cryogenic pumps or conditions. A significant portion of the literature centers on the design and installation of cryopumps, transitioning to considerations regarding safety management within cryogenic systems. Additionally, several studies have sought to advance cryogenic pump technology either through the development of novel technologies or improvements to existing ones by using experimental or simulation-based approaches. Another area of focus has been evaluating thermal and material reliability in diverse system designs operating under cryogenic conditions.

While these studies are crucial and underline the various research efforts to improve cryogenic technologies to ensure their effectiveness and safety across different scenarios, a comprehensive review of the literature reveals a limited exploration of the reliability and safety aspects of cryogenic pumps. Risk and reliability analysis has gained more attention in the past years as a way to prevent failures and downtime and minimize maintenance costs [10]. The limited number of available studies that approach cryogenic pumps from a reliability and safety engineering aspect largely lack unity in language and definition of terms; there are different methods for reliability and risk analysis such as Failure Modes and Effects Analysis (FMEA), Quantitative Risk Analysis (QRA), and Prognosis and Health Management (PHM) that not all have been adequately addressed. Moreover, these studies mostly focus on the use of oxygen, helium, and nitrogen in cryogenic environments, with hydrogen receiving scant attention. The lack of emphasis on the reliability of hydrogen cryogenic pumps may be caused by the novelty of using hydrogen as a fuel source. Although hydrogen shows significant potential for becoming a suitable green fuel option, several obstacles such as the cost of green hydrogen, lack of infrastructure, lack of codes standards, and the hydrogen storage challenges, have delayed its widespread industrial and commercial adoption [11]. However, hydrogen shows features such as high energy content per weight in comparison with other resources, having water as its only byproduct, availability within a wide variety of sources, and most importantly its huge global market that makes the adoption of hydrogen beneficial [12].

This paper aims to provide an overview of the current state of cryogenic pump reliability analysis in literature. It is crucial to address the gaps in documentation and studies as within the next few years, the demand for clean green fuel for industrial and commercial uses will keep growing, and with that comes an increased need for the reliability and safety of cryogenic pumps. Examining specific reliability and safety considerations in cryogenic pumps would enhance the understanding and advancement of cryogenic technology. By prioritizing safety and reliability in the use of cryogenic pumps, safer and more efficient technology can be ensured, especially in emerging areas such as hydrogen fueling.

In the following section, we will discuss our method for conducting this systematic literature review. It will be followed with a section on our findings within the selected papers and a more detailed exploration of the information on the reliability of cryogenic pumps. The next three sections are devoted to the discussion of the findings, our recommendations for future research, and finally an overall conclusion of the work done throughout this review.

## **2. METHODOLOGY**

Cryogenic pumps come in various types, each designed to handle different cryogenic fluids and support diverse industrial applications. We used Scopus and Google Scholar, two of the most comprehensive science search engines alongside OSTI to conduct our search.

### **2.1. Search strategy and selection criteria**

In reviewing the literature on cryogenic pumps, different studies have focused on aspects like pump design, operational efficiency, reliability, safety, and maintenance. To avoid a limited perspective or a narrow application of cryogenic pumps, we followed the expansive and iterative approach to build a comprehensive search query. This approach supports our research objective by allowing us to use broad terminologies that bridge different types of pumps, applications, and industries.

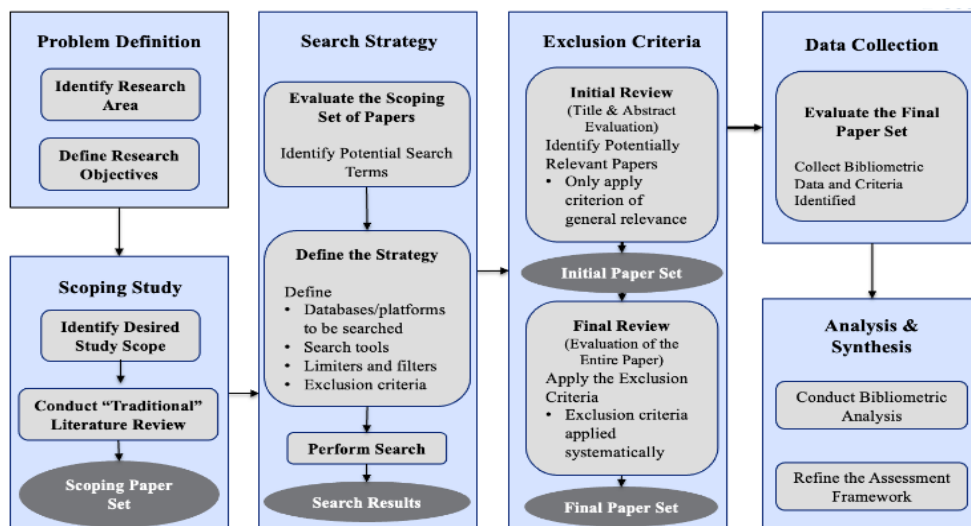
Based on this approach, we developed the following structure, consisting of a combination of different terminology sets, to use as our search query. Each set includes several synonyms for the main term, which are commonly used in various domains in the related literature, so they were separated with OR statements within the sets. The sets themselves were split with AND statements. As a result, Scopus and Google Scholar returned documents that contained one of the terms from each set. This approach allowed us to capture a wide range of studies focusing on cryogenic pumps across various industries.

Initially, 12,944 results were found with the search terms of cryogenic pump or cryopump. We restricted our search to the fields associated with the title, abstract, and keywords to capture papers whose central focus aligned with the selected search terms. The resulting 1,366 papers were then reduced to 1,266 by limiting them to only English, peer-reviewed journal articles and being published between 1990 to 2022.

This set of publications was further filtered by relevant citation topics, categories, and research areas. This resulted in 98 papers that were more focused on the scope of our research objectives. The same search process was repeated with small modifications to ensure a complete set of results. Next, the sets of papers obtained from each search and platform were merged, and duplicates were removed (those papers were indexed in both databases), resulting in 198 papers.

Finally, 91 papers were removed by title and abstract evaluation, and 35 papers were excluded by full-text screening. The exclusion criterion at this stage was that any paper whose core topic was not found relevant to the risk and reliability analysis of cryogenic pumps was removed. The remaining 72 relevant papers were then carefully analyzed following the steps in Figure 1. which are adopted from the recommendations of Keathley-Herring et al. [13] to conduct a systematic literature review.

Figure 1: Systematic Literature Review Framework adapted from Keathley-Herring et al.



## 2.2. Data extraction

In the next stage of our systematic review, we performed data extraction which involves obtaining the information from the studies reviewed. This also includes organizing the information in a way that will help to synthesize the studies and draw conclusions. To do so, we created a comprehensive spreadsheet with the following columns: Keywords, Research Objective, Field/Application Area/Industry, Data Collection Method, Case Studies (Yes or No), Sample Size, Type of Cryogenic Pump, Gas or Liquid Under Study (e.g., Hydrogen, Nitrogen, etc.), Identified Failure Modes/Failure Modes Under Study, Causes of the Failure, Consequences of Failure, Reliability Analysis Methods Used, Reliability Metrics Used, Key Findings, Any Suggestions for Improving the Reliability of the Pump, Authors' Conclusions, Suggested Future Work, and Relevance Rating (0 to 10).

By compiling this spreadsheet, we organized information in a manner that allowed us to identify patterns across studies, find recurring themes, and note areas where existing research was lacking. The extraction process helped us gain a broader view of reliability, safety, and risk analysis for cryogenic pumps.

## 3. SYNTHESIS OF FINDINGS

### 3.1 Industry distribution and pump types

The resources reviewed for this paper showed the diverse industry applications of cryogenic pumps, from liquified natural gas (LNG) and hydrogen energy to aerospace and manufacturing. These studies show the use of cryogenic pumps with different names and designs, each addressing specific operational needs and challenges. Some studies discuss centrifugal pumps that are widely used in cryogenic applications due to their efficiency and capacity to handle large volumes of liquid. We can find discussions on hydrogen in cryopumps in several studies. Shao and Zhao focus on optimizing liquid hydrogen centrifugal pumps for better performance for liquid hydrogen applications, addressing issues such as cavitation and flow instability to enhance reliability and Qiu et al. discuss new designs for hydrogen fueling stations, focusing on their synergy with cascade storage systems to ensure reliable operations [14-15]. The research conducted by Kim et al. investigates the operational performance and reliability of LH2 pumps under varying conditions, emphasizing the need for robust design to handle subcooling and other operational challenges [16]. Ageladarakis et al. examine the thermal and structural reliability of cryogenic components in their two-part study to highlight the significant implications for the hydrogen energy sector and automotive and transportation industries. They discuss the use of centrifugal pumps in accelerator applications, emphasizing thermal and structural reliability [18-19]. This is further supported by the work of An et al., who emphasize managing pressure changes between cryogenic reservoirs and pumps in transportation applications [19]. Additionally, Li et al. discuss pump performance in liquid pump-enabled hydrogen fueling systems for heavy-duty fuel cell vehicles [20].

In the aerospace industry, Starkey et al. talk about a developed pistonless rocket engine pump that aims to reduce the complexity and improve the pump performance in this industry [1]. Also, Lai et al. study the performance of cryopumps, focusing on both the static performance of hydrodynamic bearings in high-speed liquid hydrogen centrifugal pumps, which are widely used in aerospace and the optimization of inducer pumps to improve suction performance and enhance reliability in hydrostatic systems [21]. Some studies focus on applications within the broader energy sector. The research by Wright et al. on improving performance through the simulation of condition monitoring schemes highlights the importance of cryogenic pumps for energy production and distribution systems [5].

Kasuya and Yuyama study the application of refrigerator-cooled cryopumps in ultrahigh vacuum applications [22]. In the area of vacuum systems, Lessard examines the performance of cryogenic vacuum pumps in severe conditions [23]. Karpenko et al. also highlight the need for reliable remote control and monitoring systems in underground cryopump vacuum systems to guarantee continuous operation of the system [24]. Lessard examines the reliability of cryogenic vacuum pumps, operating under severe conditions, highlighting the importance of reliability assessments to prevent operational failures [23]. Bianchini et al. discuss submersible pumps, designed for underwater or in applications where maintaining a dry environment is challenging, in the context of condition monitoring as they require advanced diagnostics to detect potential failures and maintain reliability [25].

### 3.2. Application-specific reliability insights

The literature addresses the risk, safety, and reliability of systems that include cryogenic pumps from different aspects. Kumar et al. emphasize the importance of reliability and safety for cryogenic turbopumps in human space missions, particularly by conducting Probabilistic Risk Assessment (PRA) to identify and manage failure-initiating events, analyze their causes via fault tree analysis (FTA), and mitigate risks through event tree analysis (ETA) [26]. Li et al. discuss various types of losses within a Stirling cryocooler that affect the reliability of the system [27]. Petitpas et al. discuss the thermodynamic advantages of using cryogenic pressure vessels and the LH2 pump for improving the reliability of hydrogen storage and dispensing [28]. Shao and Zhao discuss the optimization design method to improve the performance and reliability of liquid hydrogen (LH2) centrifugal pumps by reducing hydraulic loss and improving cavitation resistance by modifying the geometric parameters of the pump's impeller and adding an inducer [14]. Shu et al. emphasize the importance of understanding the transient flow characteristics in liquid hydrogen pipelines to ensure reliability and safety. They discuss how the cryogenic nature of liquid hydrogen and rapid valve closures can lead to significant pressure

fluctuations and material brittleness, which pose reliability challenges [7]. The reliability and stability of the floating-ring isolation seals under various operational conditions at the fuel-supply end of a rocket engine turbopump are important factors in determining safety which Song et al. address in their study [29]. Even though Stelzer et al. do not specifically discuss general reliability insights, they emphasize safety regulations and the technical concepts implemented to handle the case of hydrogen released by an in-vessel cryopump safely [9].

Several studies provide insight into the reliability of cryogenic systems and pumps. Xiang et al. highlight that the performance of cryogenic systems to avoid system failures and ensure continuous operation, particularly those using cryogenic fluids like liquid hydrogen, is heavily dependent on the components' reliability [30]. Xu et al. examined the reliability and service life of rolling element bearings in cryogenic environments. They provide information about the design and material selection for enhanced durability and performance [6]. Chakrapani et al. investigated the reliability of cryopumps over long periods of operation specifically with a constant pumping speed. They report no degradation in the system and consider that an indicator of high reliability [31]. Chen et al. do not specifically provide insights into the reliability; they discuss the failures of vapor injection heat pumps (VIHPs) and the impact of refrigerant leakage on them [32]. Cheng et al. focus on the impacts cavitation can have on the availability, reliability, and durability of cryogenic pumps [33]. The importance of monitoring and diagnosing cryogenic pump-motor systems to enhance reliability is discussed in a study by Choi et al. In their work, they name vibration and current signature analysis as effective methodologies for detecting and preventing potential failures [34]. Cioni et al. highlight the importance of reliability in the design of cryogenic piston pumps especially if they are handling LNG and hydrogen. They mention that this needs accurate design and material selection to guarantee adequate reliability [35]. The importance of reliability in the design and operation of cryogenic compressors is discussed by Lai et al. and it highlights the need for advanced monitoring and maintenance strategies to ensure continuous operation [21]. Lessard discusses the reliability of cryogenic heat exchangers, emphasizing the need for robust design and material selection to prevent failures and ensure efficient heat transfer [23]. Mahmood et al. emphasize the importance of enhancing the reliability and efficiency of liquid ring vacuum pumps (LRVPs) by suggesting various design improvements, such as modifying the impeller blades and optimizing the discharge window [36].

There are multiple papers focusing on liquid hydrogen storage and thermal management. Ahluwalia et al. emphasize the importance of reliability in liquid hydrogen storage systems for heavy-duty applications. They highlight the challenges and potential solutions for managing liquid hydrogen under various operational conditions [37]. To focus on the thermal management of liquid hydrogen storage, An et al. talk about the importance of effective thermal insulation and pressure management in cryogenic storage and transfer systems to ensure safe and efficient operation [19]. Similarly, Yan et al. provide insights into the selection process of liquid hydrogen lubricating systems to discuss the reliability of these systems in maintaining the reliability of hydrogen storage under extreme conditions [38]. Ageladarakis et al. discuss the importance of reliability analysis in the accident simulation of cryogenic pumps in nuclear fusion systems. They emphasize their point in the second part of their study by discussing the need for reliability in mathematical modeling for their thermal simulation of cryogenic equipment [17-18]. Kasuya and Yuyama highlight the challenges of maintaining low temperatures and preventing thermal losses in liquid hydrogen storage systems [22]. Ku et al. emphasize the durability of material under cyclic thermal loading to maintain the reliability of cryogenic storage systems for liquid hydrogen [39]. Finally, Kumar et al. highlight the importance of thermal management in cryogenic hydrogen systems by highlighting the impact of thermal insulation on system reliability [40].

Another group of reviewed papers provides insights into the reliability of hydrogen fueling infrastructure and its importance in adopting hydrogen as a fuel. Apostolou and Xydis discuss the design, maintenance, operational strategies, and other factors for improving the performance and safety of a hydrogen fueling station [41]. In their study, Kim et al. focus on the reliability of hydrogen dispensers in fueling station components and the impact of environmental conditions on system performance [16]. Ku et al. emphasize integrating safety protocols and regular maintenance to ensure consistent performance [39].

From a cryopump components perspective, Zhao et al. provide a comprehensive evaluation of the silicon diaphragms in silicon-based pumping systems under various operational conditions and offer recommendations for extending the system’s reliability and service life [42]. Zhou et al. emphasize the need for robust design and testing methodologies to ensure the reliability of the design of the inlet valves for cryogenic hydrogen storage and delivery systems [43]. Qiao et al. address the wear mechanisms and failure causes to propose improvements to enhance reliability and safety in mechanical seals used in oil transfer pumps [44]. The dynamic characteristics of the pump valve system in an ultra-high-pressure liquid hydrogen reciprocating pump are studied by Qiu et al., with an emphasis on the behavior of valves and the impact of different factors on valve operation [45]. Rahbarimanesh et al. emphasize the importance of including interfacial tension forces in the modeling of a cryogenic cavitation flow of LNG inside a Laval nozzle [46].

### 3.3. Methods and reliability techniques

Among the reviewed literature, 63 utilized different approaches and methods in addressing their reliability questions. Also, 14 of the studies have used reliability engineering methods such as Quantitative or Probabilistic Risk Assessment (QRA/PRA), Failure Modes and Effects Analysis (FMEA), failure modes, effects, and criticality analysis (FMECA), hazard and operability study (HAZOP), event tree analysis (ETA), fault tree analysis (FTA), reliability block diagram (RBD), and finite element analysis (FEA). Table 1 provides a summary of the reliability methods, numerical or mathematical models, simulations, and experimental approaches used in each study. The column “Data collection method” refers to specific models, algorithms, software, or experiments they might have used to achieve the goal of their study.

Table 1: Methods used in the studies reviewed.

First Author	Year	Approach										Modeling or Data collection method	Goal	
		QRA/PRA	FMEA/FMECA	HAZOP	ETA	FTA	RBD	FEA	Math/Nume	Simulation	Experiment			
Kang [47]	2022				*	*							Petri nets and bowtie model	Modeling risk scenarios at hydrogen fueling station
Goo [49]	2019	*				*							FMECA and axiomatic design analysis	Identify and mitigate potential risks early in the design process of an LNG fuel gas system
Ageladarakis [18]	1998	*						*	*	*	*		Theoretical and experimental simulation of accident scenarios	Reliability and safety of the LH2 cryopump in the Tokamak
Ahluwalia [37]	2023	*						*					Structural analysis based on the ASME boiler and pressure vessel code	Identify and mitigate potential failure modes and ensure the safety and reliability of the LH2 storage systems
Song [29]	2023							*	*	*			Using computational fluid dynamics (CFD)	Study a two-stage floating-ring isolation seal for a high-speed turbopump
Wang [50]	2023							*	*	*			Neural network regression (NNR), Monte Carlo simulation, and sensitivity analysis	Reliability analysis of reusable turbine rotor blisk
Wu [51]	2022							*	*	*				Study the influence of main motor parameters on the performance and power density of a cryogenic cooling system of an electric rocket pump driving system

Howell [52]	2015	*																	Using DataStream software	Identify and prioritize risks and preventative maintenance programs
Wright [5]	2014	*																	Using fault detection and isolation (FDI) scheme	Estimate plant process variables and detect faults of a condition monitoring scheme for a neutral beam injector cryogenic pump
Zhou [43]	2023							*		*									Analyzing and simulating using the Monte Carlo method, ANSYS software, and seismic analysis	Design and analysis of the inlet valve for cryopump
Cai [53]	2007							*											ANSYS Solid95 elements for analyzing the stress and displacement levels	Ensuring pump reliability under different loading conditions
Ageladarakis [17]	1998								*	*	*								Accident monitoring using implemented safety systems	Address the accident scenarios of an in-vessel cryopump
Chakrapani [31]	2007								*	*	*								Monte Carlo simulation and conducting tests using H2	Profiling the long-term pumping behaviors
Shao [54]	2020								*	*	*								CFD and Zwart Cavitation Model	Study the flow in a cryogenic pump under different cavitation inducements
Shao [14]	2024								*	*	*								Speed coefficient method, loss extremum method, criterion screening method, and CFD	Improve cavitation and reduce hydraulic loss in LH2 centrifugal pump
An [19]	2021								*	*									Lee-Kesler equation for state computations and Euler's linear multistep method for pressure calculations	Investigate NPIP management in cryogenic high-pressure reciprocating pumps
Chen [48]	2021								*	*									Numerical simulation of cooling performance	Performance analysis of precooling processes at hydrogen fueling stations
Cannella [55]	2013									*	*								Simulating the cycling and sizing of the pump chambers using MATLAB. Experiments such as ground tests, cryogenic fluid testing, and rocket engine burn tests	Validate the functionality and reliability of the in-space pistonless pump technology
Chen [32]	2023								*	*									Dynamic modeling, numerical simulation, and parametric analysis	Analysis the impacts of leakage on the performance of a pump
Chen [56]	2023								*	*									Large eddy simulation (LES) and the Singhal cavitation model	Simulate unsteady cavitating flows in a cryogenic inducer
Fan [57]	2022								*	*									Using the Singhal cavitation model	Predicting pressure fluctuations and investigating cavitation performance and instability in cryogenic inducers
Fu [8]	2023								*	*									Gaussian Process Regression (GPR) models, stochastic simulations, and variance-based sensitivity analysis. Reliability techniques include Bayesian Updating with structural reliability, adaptive importance sampling, and efficient structural reliability analysis	Predicting and optimizing cavitation characteristics in pumps
Hu [58]	2023								*	*									Application of lumped parameter method and temperature partition method. Using a 2D axisymmetric swirl model and commercial CFD software ANSYS Fluent 16.0	Verifying the accuracy of the temperature partition method for cryogenic cold energy recovery in liquid hydrogen refueling station
Lai [21]	2023								*	*									Employing an orthogonal design method for optimization, the modified ZGB cavitation model, SIMPLEC, and PRESTO! Algorithms, and numerical analysis	Evaluate the static performance of hydrodynamic bearing in high-speed liquid hydrogen centrifugal pumps

Li [59]	2012							*	*	Utilizing numerical simulation, finite element methods, Solidworks, and Fluent for CFD	Evaluate the cryogenic pump's temperature profile under various conditions
Li [60]	2024							*	*	Using the SST k- $\omega$ turbulence model, two-fluid model, and entropy production diagnostic model (EPDM)	Identify the characteristics of cavitation flow in LNG cryopumps
Park [61]	2022							*	*	Numerical modeling using SAGE software. Following ISO standards for vacuum pumps for performance evaluation	Development of a large capacity cryopump
Petipas [28]	2018							*	*	Thermodynamic fill model and detailed physics-based models	Ensure the reliability of hydrogen storage and dispensing using cryogenic pressure vessels and the LH2 pump

### 3.4 Identified reliability issues

Of the 72 reviewed papers, 66 include reliability issues found within the cryogenic systems they studied. Specifically, 26 of them report the reliability challenges related to hydrogen. Table 2 summarizes the most frequently named issues among the studies for different pumps, components, and cryogenic situations. The most repeated terms are cavitation and leakage.

Table 2: Identified reliability issues and failures

Author	Identified Issues							
	Cavitation	Thermal Effects and Heat Transfer	Mechanical Failures and Wear	Leakage	Pressure and Flow Instabilities	Reliability of Materials under Cryogenic Conditions	Control and Sensor Failures	Noise and Vibration
Fan et al. [57], Fu et al. [8], Kim et al. [68], Mahmood et al. [36], Opitz & Schlücker [69], Vermes et al. [71], Wan et al. [64], Wang et al. [65], Kumar et al. [40], Shao et al. [54]	*							
Kang et al. [67], Qiao et al. [44], Song et al. [29], Genovese and Fragiaco [72], Ku et al. [39], Stelzer et al. [9]				*				
Karpenko et al. [24], Kasuya & Yuyama [22], Yan et al. [38]						*		
Bianchini et al. [25]	*		*					*
Braylovskiy and Blyukher [66], Lessard [23]		*						
Cai et al. [53]					*			
Chen et al. [32]		*					*	
Choi et al. [34]			*					
Conde et al. [2]			*					
Li et al. [27]		*			*			*
Suh et al. [70]								*
Wright et al. [5]			*				*	

Zhao et al. [42]			*					
Ahluwalia et al. [37]				*			*	
An et al. [19]							*	
Chakrapani et al. [31]				*				
Cioni et al. [35]	*	*		*	*			
Puthettu Muraleedharan et al. [73]					*			
Qiu et al. [15]	*				*			
Shao and Zhao [14]	*	*						
Shu et al. [7]				*		*		
Xu et al. [6]			*			*		*

#### 4. DISCUSSION

Synthesizing the information extracted from the reviewed studies shows diversity in the areas of focus with a lack of a unified taxonomy in describing the failures and the process leading to them. From a reliability engineering perspective, failures are discussed based on their mechanism (the process leading to the item's failure) and their mode (the way the item fails) [10]. Based on our understanding of the most common issues discussed in the studies, we categorized them into failure mechanisms and modes in Table 3. These failure modes represent an aspect of the causal chain in the failures that can occur within a cryogenic system.

Even though hydrogen is considered one of the in-demand sources of clean energy, few studies are entirely devoted to the subject as they need field and experimental data which is not easily available due to the nature of the hydrogen.

Table 3: Failure modes and mechanisms	
Failure Mechanism	Failure Mode
Cavitation	Surface damage in flow components
	Overheating
Wear	Leakage
	Contamination
	Loss of pressure
	Increased friction
	Vibration
	Rotating equipment failure (overspeed, under-speed, fail-off)
	Crack
Yielding	Breakdown
	Deformation
	Breakdown
Corrosion	Breakdown
Fatigue	Crack

#### 5. RECOMMENDATIONS, POTENTIAL FUTURE RESEARCH, AND CONCLUSION

As cryogenic pumps become increasingly important as part of emerging hydrogen infrastructure, there is a need for new studies to enable increasing the reliability of these pumps. The first step toward this is understanding the reliability issues observed in cryopumps and characterizing their failure modes and mechanisms. We have assembled the first review of failure and reliability models for cryogenic pumps to provide a starting point for future reliability and risk modeling efforts. Given the data on hydrogen cryogenic systems, the taxonomy can be expanded to cover a bigger range of reliability issues. This helps the development of reliability models and frameworks such as FMEA, Quantitative Risk Analysis (QRA), and PHM. By prioritizing reliability and safety in using cryogenic pumps, safer and more reliable technology can be ensured for emerging hydrogen fueling.

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