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SAFETY AND RISK MANAGEMENT IN THE CONSTRUCTION INDUSTRY OF CRYOGENIC AIR SEPARATION PLANTS

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Abstract: Safety and risk management are important concepts in construction of Cryogenic Air Separation Plants (CASP). Conventional Hazard Identification and Risk Assessment (HIRA) methods have proven ineffective in practice since many crucial aspects like structured safety management frameworks are often not taken into account. This study develops and integrate STARR Model (Select - Train - Assess - Review - Reinforce) into CASP construction Safety Management System (SMS) along with a comprehensive construction phase-wise HIRA process. The study emphasizes mechanism enhancement for hazard control, safety compliance, and the promotion of a strong safety culture in CASP projects. A multi-phase methodology has been employed, which included survey methods, expert reviews, and analysis of safety practices at a CASP construction site in North India. STARR Model ensures proactive safety measures through systematic workforce training, risk assessment, and continuous improvement, while the HIRA process is aimed at identifying, evaluating, and mitigating risks throughout all phases of construction. Results demonstrated that the integration framework is effective in incident reduction, regulatory compliance facilitation, and safety culture enhancement. It is concluded that the proposed model greatly enhances safety performance in CASP construction but is at present limited to application in one project. Further studies may explore wider industry implementations of the model, together with the incursion of advanced safety technologies into risk management, thereby enhancing sustainability in high-risk construction environments.

Keywords: Cryogenic Air Separation Plant, Construction Safety, Safety and Risk Management, Hazard Identification, Risk Assessment.

1. Introduction

Construction safety is imperative for high-risk industries such as the construction of Cryogenic Air Separation Plant (CASP) where there is complicated work, heavy equipment usage, hazardous gases, and extreme temperatures. Both safety and risk management need to be incorporated so that incidents may be avoided as missing links within systematic safety processes may have resultant drastic

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consequences ranging from work conflicts, unsafe workplace procedures, danger of fire outbreak, gas leakages, to cryogenic exposure. Construction safety management effectiveness is closely related to the efficiency of overall project management [1]. Strong Occupational Health and Safety (OHS) practices not only reduce incidents but also enhance worker morale, project efficiency, and adherence to regulatory standards [2]. But traditional Hazard Identification and Risk Assessment (HIRA) techniques assess risk mainly on the basis of severity and likelihood but tend to neglect key considerations such as exposure frequency and legal standards, and hence risk mitigation measures are restricted [3]. Construction projects with ill-organized risk management systems have increased fatality rates, delays, and inefficiencies, especially in areas where conventional approaches prevail over organized safety procedures [4]. Sophisticated safety models, like the Bayesian Belief Network (BBN), offer predictive functions for risk assessment and mitigation, and hence are a vital tool for enhancing hazard control in dynamic construction settings [4]. In addition, structured risk assessment methods such as HIRA and Job Safety Analysis (JSA) have been found effective in manufacturing environments, but their potential is yet to be realized in CASP construction [5]. Hence, in this study STARR Model is integrated within safety management system and a detailed step-by-step Hazard HIRA is applied across all key CASP construction & commissioning phases of CASP. The STARR model requirements are more significant for CASP construction where a stringent planning and execution is crucial to make workplace safe and secure.

2. Literature review

These studies reveal that digital tools improve safety in general but are especially important for migrant workers, although their effectiveness is usually limited to certain areas [6]. Likewise, Construction Safety Management Information Systems (CSMIS) facilitate risk compliance, but these systems are not widely utilized in CASP projects [7].Integrated Management Systems (IMS) foster sustainability and mitigation of risks through real time monitoring and intervention. But these systems are not tailored for CASP commissioning that has specific safety issues [7].Although there are precautions like railings and safety nets, construction falls continue to be a significant contributor to construction site injuries [8]. Safety training, observation, and PPE usage are important, but current research fails to consider CASP-specific risks such as cryogenic injury, confined space entry, and oxygen deficient environments [8]. If there are aspects of an organization that could affect strategy, risk assessment and management, then those areas are the specific allocation of resources, the complexity of the site, and the management model since they have fundamental importance to safety [9]. The problem of resources and meeting OHS requirements places developing countries behind their counterparts since

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there isn’t enough money, workforce, and regulations [10].High risks industries, such as nuclear power plants, offer valuable lessons on the risk assessment strategies that CASP projects can benefit from [11]. Unlike hazard risky class systems of CASP application, Set Pair Analysis (SPA) and Trapezoidal Fuzzy Number (TPFN) are often put to more use, but their incorporation into CASP did not happen [11]. Deficiencies in the literature related to safety aspects within the scope of new construction include the launch phase where new possibilities emerge together with the new risks of system testing and operational handover [12]. Construction hazards include classifications such as financial, safety, design, and operational issues that need well-planned prevention and corrective measures [13]. But, the effective management of risks is still lacking in most areas which have a poorly defined regulatory structure and skill gaps [14].

The above literature review shows that many studies focusing on construction safety and risk management, but not a single one of them adequately discusses CASP construction projects with in a methodical framework to manage and integrate safety from initial stage to completion of a CASP construction, also commissioning activities of CASP are yet another area that is not dealt with when it comes to risk mitigation. Construction safety is driven by leadership & management team and it is always a top-down approach, hence both teams must be safety-oriented and efficient in planning and setting targets for effective safety implementation and risk management from the initial stage of CASP construction projects, however this aspect is not strategically addressed in the literature review. The absence of these measures deserves acknowledgement and, therefore, calls for proper, specialized industry safety and risk management models to enhance CASP construction safety and other related outcomes.

3. Objective of the Study

The aim of the study is Integrating the STARR Model into the Safety Management System (SMS) of CASP Construction to enhance control of hazards, enhance safety compliance and develop a robust safety culture in CASP construction projects. Further, the research also determines phase-wise construction activities, the possible hazards and their control measure utilizing eight steps of HIRA process to supplement the STARR model. This study also aims to prevent safety incidents and to promote safer operations for CASP construction projects by adopting structured safety models and proactive risk assessment techniques. The intention as framed by author is to improve safety and risk control in CASP construction and guarding of workforce.

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4. Methodology

This study adopts a structured safety management approach by integrating the STARR Model (Select - Train - Assess - Review - Reinforce) into the Safety Management System (SMS) of CASP construction as shown in Figure 1. To complement this framework and manage the associated risk, a detailed step-by-step Hazard Identification and Risk Assessment (HIRA) is applied across all key CASP construction & commissioning phases as shown in Figure 2. Study ensure that all potential hazards are systematically identified, assessed, and controlled at each stage of the construction process. This study focuses on examining the safety and risk management aspects of Cryogenic Air Separation Plant (CASP) construction project in North India. A multi-phase approach to collecting data was followed to cover every aspect of safety practices and to assess potential gaps. A questionnaire survey was administered to designing engineers, construction-and-commissioning managers, civil, mechanical, and electrical engineers, execution supervisors, foremen, and workers. The objective was to assess their perception of safety and risk management existing practices at the CASP construction site and identify areas needing enhancement. Supporting the findings, risk management data were collected from work method statements, HIRA, and JSA reports. A second level of discussion was conducted with safety managers, engineers, and supervisors about integration of the STARR Model (Select - Train - Assess - Review - Reinforce) into safety management and a detailed and systematic application of the HIRA process. To strengthen the validity of the study framework, an expert review with 30 professionals specializing in safety and risk management in CASP construction was conducted. The inputs from these experts were used to fine-tune the proposed safety framework to improve its applicability in practice.

4.1 Enhancement of Safety Management Using STARR Model

The STARR Model is a structured safety management framework designed to increase risk control, competency of workforce and continuous improvement in CASP construction. This follows a systematic cycle of Selection, Training, Assessment, Review and Reinforcement, and ensures that safety measures are proactively identified, implemented, evaluated and sustained in the construction cycle. By integrating this model, the purpose of study is to strengthen hazard control, improve compliance and establish a resilient safety culture in CASP construction projects.

There are five steps in STARR Model to enhance safety management in construction of CASP

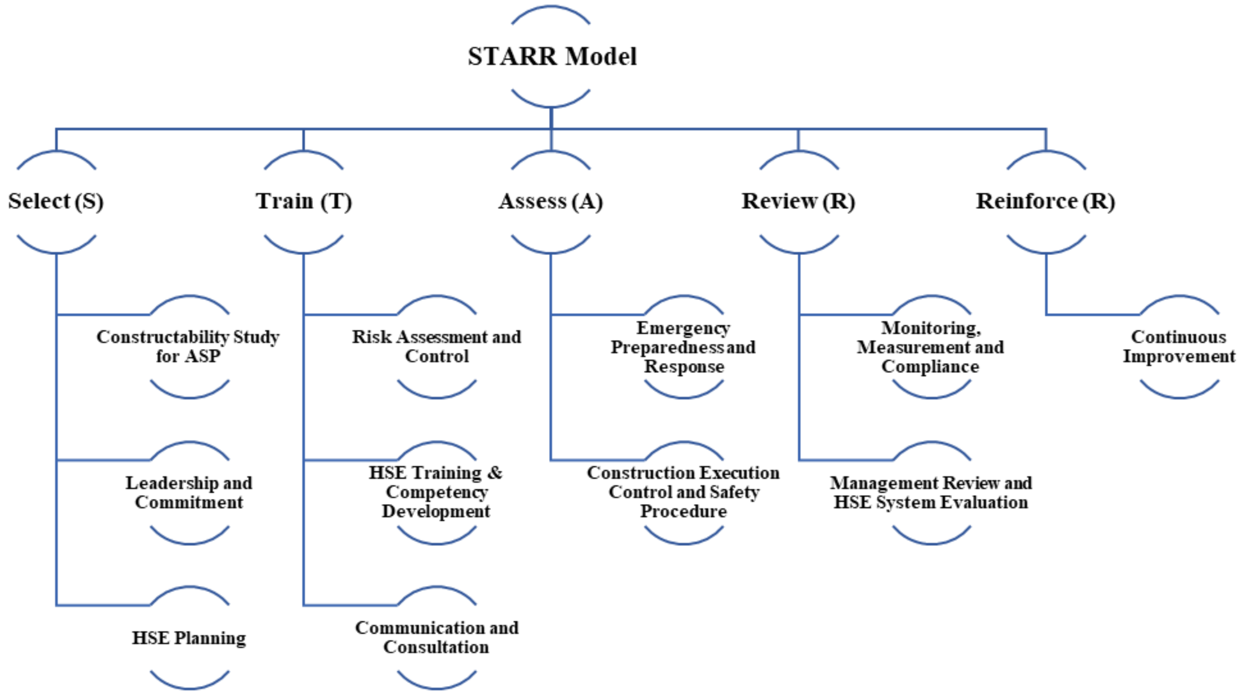

Figure 1: STARR Model for Enhancing Safety Management System

A. Select- Refers to identifying and selecting the essential safety prerequisites, including site conditions, design optimization, material handling strategies, workforce readiness, regulatory compliance, and HSE policy framework, to establish a strong foundation for safe CASP construction.
B. Train- Refers to developing workforce competency through safety training, risk awareness, emergency preparedness, and procedural adherence to ensure effective hazard control in CASP construction.
C. Assess- Refers to evaluating emergency preparedness, risk control effectiveness, safety engagement, and incident reporting to ensure continuous safety improvements in CASP construction.
D. Review- Refers to analysing safety performance, auditing compliance, investigating incidents, and identifying improvements to enhance risk management in CASP construction.
E. Reinforce- Refers to strengthening the HSE system by updating policies and procedures, aligning with best practices, and ensuring continuous improvement in CASP construction safety.

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4.2 Detailed Step-by-Step Hazard Identification and Risk Assessment (HIRA)

HIRA is a systematic process that proactively detects potential workplace hazards, evaluates their risks, and establishes control measures to minimize incidents. It provides a structured framework for analysing task-specific dangers, ensuring worker safety, enhances decision-making in dynamic work environments and help to maintain regulatory compliance. This approach optimizes hazard control, improves safety culture, and reinforces continuous risk management in high-risk industries like CASP construction.

Eight step process is followed to implement HIRA, across all key CASP construction phases.

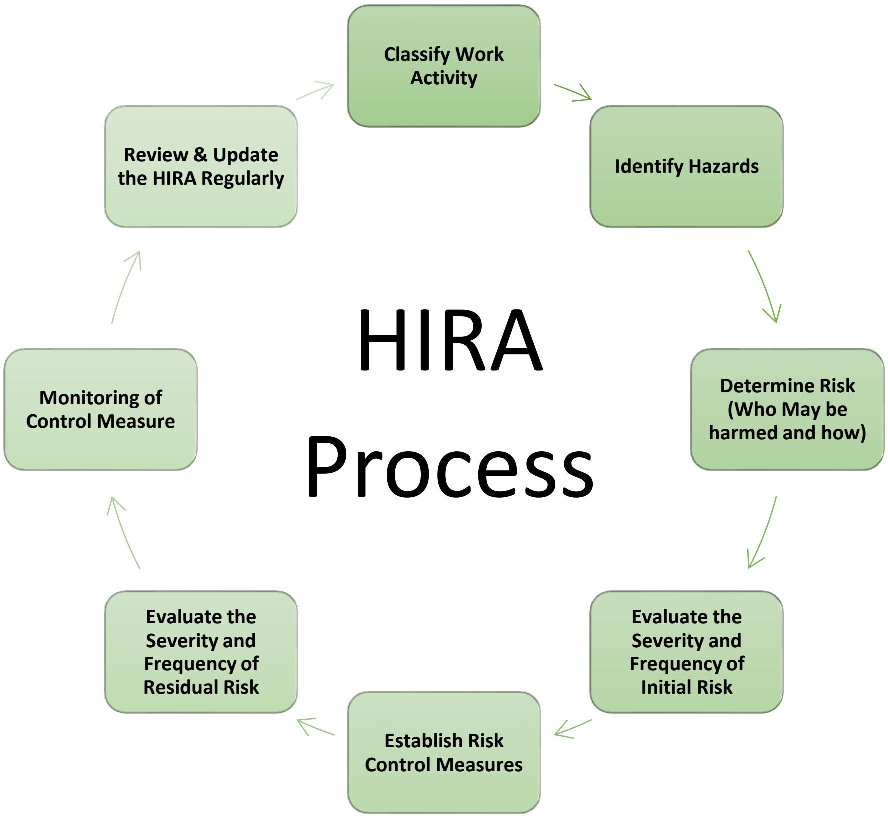

Figure 1: Eight Steps of HIRA Process

i) **Classify Work Activity**

The first step in the HIRA process is categorizing work activities based on the phases of CASP construction, complexity, and associated hazards. This classification ensure that each task is analysed systematically, considering all aspects of CASP construction, from site preparation and structural assembly to commissioning and final handover. Proper classification allows for targeted hazard identification, ensuring that high-risk activities such as cryogenic handling, heavy lifting, and confined space work receive focused attention.

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ii) Identify Hazards

After classification of work tasks, a proper identification of possible risks are done for every task. This covers all possible physical, chemical, biological, ergonomic, and process related risks that can be posed risk to the workforce, equipment, and the environment. In CASP construction, the hazards of oxygen enrichment, extreme cold, high-pressure systems as well as working at heights are considered in order to avoid incidents. At all phases of the construction process, hazard identification that allow risks to be addressed will be ongoing.

iii) Determine Risk (Who May be Harmed and How)

After hazard identification, the next logical step is to analyse the consequences and evaluate who may be affected. This involves assessing job roles, exposure levels, and the likelihood of harm to workers, contractors, and surrounding personnel. In CASP construction, workers such as welders, riggers, and operators handling cryogenic equipment face specific risks, requiring tailored safety measures. The risk assessment process ensures a thorough understanding of potential injury severity and construction execution disruptions.

iv) Evaluate the Severity and Frequency of Initial Risk

After identifying hazards, the next step is to evaluate the severity and frequency of each risk to determine its initial level before any controls are applied. This uncontrolled risk known as the initial risk, is assessed based on how frequently it may occur and how sever its consequences could be, as illustrated in table-2 and 3. This helps prioritize which risks need immediate control actions. High-risk activities like Height work, lifting operation, cryogenic handling, oxygen-enriched environments, hydro & pneumatic testing and radiography testing often rate high in both severity and likelihood. This initial evaluation ensures that risk control measures are based on a structured and data-driven understanding. It plays a crucial role in focusing safety efforts where they are most needed.

v) Determine Control Measures

After risk determination is completed, particular control measures are developed to either eliminate the risks or deal with them in a more reasonable and effective manner. Whenever identifying control measures, the hierarchical order of control measures is followed wherein elimination, substitution, engineering, administration, and personal protective equipment (PPE) in that order are considered first.

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vi) Establish Risk Control Measures

Base on the risk determination and evaluation a structured risk control measures are established. Whenever identifying control measures, the hierarchical order of control measures is followed, wherein elimination, substitution, engineering, administration, and personal protective equipment (PPE) in that order are considered first. In CASP construction, the control measure outlines the roadmap for implementation: safe work procedures, risk mitigation strategies, emergency processes, regulatory compliances, team responsibilities, resources required, communication flow between HSE, operations, and contractor teams. Henceforth, these control measures guide for the actual implementation to make HIRA process effective.

vii) Evaluate the Severity and Frequency of Residual Risk

When control measures are completely established, the level of remaining risk known as the residual risk, is assessed. This verifies that the controls that have been implemented are adequate to bring the risks down to an acceptable level. In addition, a risk class is determined after combining frequency and severity levels to assess the residual risk and it ensure a systemic approach for further risk reduction techniques, as illustrated in table-4.

viii) Monitoring of Control Measures

The site is now equipped with planned control measures which have been fully established on construction site. After, continuous monitoring makes it assured that all the controls are functioning as designed. Regular site inspections, safety monitoring in real-time, and compliance checks for workforce are conducted. In CASP construction, this includes auditing and inspecting confined space entry procedures, verifying functionality of pressure relief system, and ensuring that workers adhere to PPE requirements. Any violation of control implementation triggers immediate corrective actions. Thus, monitoring helps to ensure safety compliance without failure and deviation from the expected standard

ix) Review and update the HIRA Regularly

The final step in the HIRA process involves periodic reviews and updates to the HIRA. As construction changes its phases, new risks may involve due to changes in site work environment conditions, equipment usage, or workforce dynamics. Lessons learned from near misses, incident investigations, and regulatory updates are incorporated into the risk control plan. In CASP construction, safety reviews will be aligned with project milestones, confirming that risk management strategies remain adaptive and effective until project handover.

5. Results and Discussion

5.1 Affirmation of STARR Model in Safety Management of CASP Construction

To establish the STARR Model, the key aspects are explained through criteria and implementation measures for an effective and stringent safety management system tailored to CASP construction.

Table 1: Affirmation of STARR Model

Key Aspects	Criteria	Implementation Measures
Constructability Study for CASP	Site Condition and Layout	Evaluate access to the site of construction equipment, materials and personnel, assess the basic conditions for foundation requirements and potential GEO -technology challenges, ensure enough space for construction activities, storage and construction activities, consider local climate, seismic activity and other environmental conditions that can affect construction.
	Design Review and Optimization	Verification of design alignment with the viability of the construction, determining whether the modular construction is possible to reduce work on the site that can pose for extra risk, adapt the layout for easy construction, installation and construction operations, can create plans and other tools for effective routing of pipes, cables and other tools, to reduce and reduce delay.
	Material Handling and Logistics	Provide important materials and timely availability of equipment, plan to transport large or heavy on-site equipment, crane selections and large cryogenic tanks, distillation column cold boxes, heat exchangers, and identify areas of exclusion to prevent accidents, identify adequate storage areas for materials and equipment to prevent damage and theft.
	Construction Method and Sequencing	Develop a phase-wise construction sequence for mechanical, electrical and instrumentation activity, plan effective coordination between different tasks groups to avoid clashes, identify pre-assembled, design and modularization options to reduce work on the site, plan for temporary facilities such as offices, fabrication yard, and laydown areas.
	Utilities & Infrastructure Readiness	Make sure the availability of temporary power, water supply and drainage during construction, set up roads and routes for ease of transportation, plan for welfare facilities such as hygiene, first aid and relaxing areas.
	Workforce and Resources	Make sure the availability of skilled workforce for special tasks such as welding, instrumentation, lifting/rigging and electrical functions, consider accommodation and transport for workers if the site is remote.
	Regulatory and permitting Requirements	Identify all necessary permits and approvals required for construction, and make sure they come in time as to ensure compliance with local, national and international codes and standards
Leadership & Commitment	Define HSE Policy	Establish a clear and structured HSE policy outlining safety objectives, legal compliance, and risk management principles. Ensure adaptation with best practice and organizational goals, and emphasizes an active safety culture at all levels of CASP construction.
	Assign Roles and Responsibilities	Assign HSE responsibilities throughout the organization while ensuring accountability at every level. Create roles for hazard recognition, incident reporting, emergency action, and regulatory compliance for site manager, supervisors, and safety officers amongst other staff.

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	Management Commitment	Show management support for HSE initiatives through active participation, resource allocation and enforcement of policies. Make sure management promotes safety culture by integrating HSE into decision -making processes, carrying out regular safety reviews and for strengthening compliance and continuous improvement with workers.
HSE Planning	Identify Legal Requirements	Ascertain all relevant legislation associated with construction of CASP, including occupational health, environmental protection, and safety compliance. Also, ensure that international and local legal requirements are followed by applying for the relevant licenses, approvals, and permits needed before commencing the project.
	Conduct HIRA	Perform a structured Hazard Identification and Risk Assessment (HIRA) to evaluate potential risks associated with each construction phase. By classify work activities, identify hazards, assess risks, and define appropriate control measures to mitigate incidents, ensuring a systematic approach to workplace safety.
	Develop HSE Plan and ER Plan	Develop an HSE Plan with risk management strategies and training as well as compliance management. At the same time, formulate an Emergency Response (ER) Plan and lay down the strategies for implementation during fire, medical, chemical, and rescue emergencies in an effort to ensure response preparedness to critical situations.
Risk Assessment and Control	Perform JSA	Conducting a Job Safety Analysis (JSA) for each activity involves estimating the potential risks and hazards, calculating risks, and outlining any required safety measures for the task at hand. Remember to communicate the results of the JSA to the workforce in order to mitigate risk exposure.
	Safe Work Procedure	Create and implement comprehensive Safe Work Procedures (SWPs) for specific tasks that present a significant risk to safety. Ensure compliance to specific safety measures because deviations from the norm compromise safety. Procedures should be reviewed and amended after a given period based on the conditions present in the site and what had been learned previously.
	Implement and monitor Control Measure	Apply risk control measures based on the hierarchy of controls and continuously monitor their effectiveness through inspections and compliance checks. Modify or reinforce controls as necessary to maintain a safe work environment.
HSE Training & Competency Development	Induction and Job Safety Training	Provide comprehensive safety induction for all personnel before entering the worksite, covering site-specific risks, emergency procedures, and safe work practices. Ensure training is tailored according to the procedure the worker will be part of.
	Specialized and Regulatory Training	Strategic compliance training must be put in place for any worker required to operate in areas with dangerous conditions, such as confined spaced, extreme heights, electrical shock risk zones, dealing with hazardous chemicals, or any other high-risk activities. Ensure workers have the necessary credentials before they begin.
	Training Assessment	Multiple approaches to be taken to assess workforce competency, like self-assessment, skill tests, feedback, and instruction discussions to check basic understanding and the assumed effectiveness of the training. Ensure training is focused, so that people can be re-trained or moved up a competency ladder.

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Emergency Preparedness and Response	Medical Response	Set up on-site medical facilities and assign responders for immediate first-aid. Implement medical examinations, emergency treatment, and evacuation for injured workers.
	Fire and Explosion Prevention	Identify fire and explosion risks associated with cryogenic storage, electrical installations, and fuel handling. Establish firefighting equipment and perform fire risk evaluations.
	Emergency Mock Drills	Regularly conduct mock drills for fire, medical, and chemical spill scenarios to assess emergency preparedness. Review response times and the effectiveness of communication and personnel cooperation.
Communication and Consultation	HSE Meeting	Organize routine HSE meetings to discuss safety performance, share incident learnings, and capture employee feedback a routine process. Facilitate all staff participation from all levels of the organisation.
	Reporting and Documentation	Maintain detailed records of incidents, near misses, safety observations, and compliance reports. Ensure all documentation is systematically recorded for audits, regulatory reviews, and performance evaluation.
	Employee Participation	Encourage active participation in HSE initiatives or hazard reporting, foster a HSE culture while contributing towards continuous improvement by providing recognition or reward for proactive safety behaviours.
Construction Execution Control and Safety Procedure	Validation of Competency and Authorization	Verify that personnel with critical authority in project tasks along with assigned work possess the requisite skills, certificates, and clearances prior to assignment. Schedule periodic evaluations of competence and limit high-risk activities to those who are authorised only.
	Permit to Work System	Implement a defined Permit to Work (PTW) system for each job like hot work, working in a confined space, or electrical maintenance. Ensure that all control plans are implemented prior to the issuing of permits.
Monitoring Measurement and Compliance	Site Inspections and Survey	Carry out routine inspection of the site as well as safety inspection to discover risks, validate processes, and check practices against established safety rules. Resolve non-conformities without undue delay through remedial action.
	Leading and Lagging Indicators	Use both leading indicators (training completion, safety observations) and lagging indicators (incident rates, Lost Time Injuries) to audit safety performance and take timely action to avert a situation.
	Incident Reporting and Investigation	Create a clear incident reporting procedure for all events and conduct a thorough investigation into each incident. Construct appropriate actions to rectify and prevent the occurrence based on derived conclusions.
	Internal and Regulatory Audit	Schedule and execute internal audits on a defined basis to evaluate how the HSE system is being used and its alignment with regulations. Take actions as required to changes and improve policies based on the audit findings.
Continuous Improvement	Performance Review	Evaluate overall HSE performance based on key safety metrics, compliance reports, and incident trends. Identify areas for improvement and implement necessary changes to strengthen the safety framework.
	Corrective Actions	Develop and track detailed corrective action plans for instances of nonconformance, unsafe behaviour, and other recurring incidents. Assign responsibility for action, examine the post-implementation outcome, and ensure accountability through follow-up reviews.
	Innovative Safety Practices	Make use of cutting-edge safety techniques like digital monitoring, web-based tracking and record keeping to improve the safety performance. Foster creativity in safety strategies for the purpose of achieving better outcomes.

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Management Review & HSE System Evaluation	HSE System Review	Conduct scheduled reviews of the whole HSE management system to ensure its adequacy in relation to the current status of the project, changes in the regulations, and the established industry standards.
	Update Policy and Procedure	Make scheduled changes in the HSE policies and procedures due to new risks, incidents, and changes in regulations. Make sure that the changes are communicated throughout the organization.
	Align with Best Practices	Relentlessly benchmark safety performance with industry standards, utilizing local and international safety standards as well as lessons from high-performing projects to drive continuous improvement in CASP construction safety.

Table-1 systematically underscored key aspects, criteria, and implementation measures to enhance safety & risk management, and regulatory compliance. This framework combined best practices, active preparedness, and continuous monitoring. Therefore, it facilitates risk mitigation and improvement concerning occupational safety. This table primarily provides strategic approach for decision-making and competency development and also commits management to construction safety. Strengthening the study by providing a practical and actionable model for improving HSE performance and reducing incident in CASP construction projects has proven to be a strength.

5.2 HIRA for Phase wise Construction of CASP

Phase-wise construction activities including commissioning and testing of CASP were consider to evaluate potential hazards. Risk associated with each phase along with their consequences are identified. Corresponding control measures and residual risk classifications ensure effective hazard management, contributing to a safer construction environment.

Table 2: Level of Frequency - Guidance Criteria

Frequency Level	Probability	Event Occurrence (Events / Per Year)	Qualitative Equivalent
5	Frequent	$F > 1$	Scenario Can Happen once or more times per years.
4	Possible	$10^{-1} < F \leq 1$	Scenario has a high likelihood of happening in a year. For, similar construction industry the event has probably happened in the last five years.
3	Occasional	$10^{-3} < F \leq 10^{-2}$	Scenario likely to happen within the life of similar construction industry. Current personnel may have knowledge, but no experience of its occurrence.
2	Rare	$10^{-4} < F \leq 10^{-3}$	Scenario may happen within the life of similar construction industry. It may have happened in the life of directly similar industry internal or external to the company.
1	Improbable	$F \leq 10^{-4}$	Scenario unlikely to happen within the life of similar plant construction.

Table-2 defines the level of frequency for potential events in CASP construction based on probability, annual event occurrence, and qualitative descriptions. It categorizes frequency into five levels, from

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"Frequent" (5) to "Improbable" (1), providing a structured approach to assess event likelihood. This classification aids in risk evaluation by aligning hazard probability with industry-specific experiences and historical data.

Table 3: Level of Severity - Guidance Criteria

Severity Level	Impact	Potential For -Onsite Injuries and Illness (One or More of the Consequences Below)	Environment and Other Effect (One or More of the Consequences Below)
5	Catastrophic	Multiple Fatalities	A catastrophic release of hazardous material with potential for: ➢ Catastrophic contamination of air/ water / land ➢ Extensive community evacuation.
4	Severe	➢ One Fatality ➢ Multiple Permanent Disabilities	A release of hazardous material with potential for: ➢ Severe contamination of air/ water / land
3	Extremely Serious	➢ Single Permanent Disability (Any Amputation, Facture of Spine, Loss of sight) ➢ Multiple Lost Time (Days Away from Work) Injury/Illness	A release of hazardous material with potential for: ➢ Reportable breach of regulatory requirements for emissions or discharges that go off-site ➢ Major damage to rivers/sea or land resulting in significant recovery time (days)
2	Serious	➢ Single Lost Time (Days Away from Work) Injury/Illness ➢ Multiple First-Aid Injuries/Illnesses	A release of hazardous material with potential for: ➢ Workplace/Community notification only ➢ No impact to the Workplace/Community ➢ Significant environmental impacts or public concern
1	Minor	Single First-Aid Injury/Illness	A release of hazardous material with potential for: ➢ Non-exceedance of permit limitations ➢ HAZMAT / ER response activated ➢ No impact to property or assets

Table-3 categorizes the severity levels of potential hazards in CASP construction based on their impact on human safety and the environment. It defines five severity levels, from "Minor" (1) to "Catastrophic" (5), considering onsite injuries, fatalities, environmental contamination, and regulatory consequences. This classification provides a structured approach to assess and prioritize risks for effective mitigation strategies.

Table 4: Risk Ranking Criteria

Frequency Level (F)	Severity Level (S)	Risk Rank (R=FXS)	Risk Class	Risk Reduction Measures
5	5	20-25	Extremely High Risk (Stop Activity until Risk is Reduced)	Stop work/activity and implement risk reduction control measure before restart, mitigate risk to “4-8”.
4	4	15-19	High Risk	Implement immediate interim protective measure and develop written action plan to reduced risk, continued

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			(Risk Must be Reduced)	activity requires written approval from Site Manager /in charge person. Mitigate risk to "4-8".
3	3	9-14	Medium Risk (Risk to be Reduced)	Implement additional protective measures, and ensure close supervision of activity by competent person or responsible authority. Mitigate risk to "4-8".
2	2	4-8	Tolerable with Controls	Validate existing control measures are in place, and effective
1	1	1-3	Tolerable as-is	None Required

Table-4 defines risk ranking criteria by combining frequency and severity levels to determine risk levels in CASP construction. It categorizes risks into five levels, from "Tolerable as-is" to "Extremely High Risk," specifying required control measures for each. This structured approach aids in prioritizing hazard mitigation and ensuring effective risk management.

Table 5: Hazard Identification and Risk Assessment

S. No	Activities	Potential Hazards	Consequences	Initial Risk F	Initial Risk S	Initial Risk R =FXS	Risk Control Measures	Residual Risk F	Residual Risk S	Residual Risk R =FXS	Risk Class
1.	**Constructability Study**										
1.1	**Team formation for design review, construction method and sequencing**	Incompetent team	Failure to provide intended outcomes	4	4	16	i) Appoint authorised and experience personnel, who has experience of similar industry	1	4	4	Tolerable with Controls
		Poor coordination between design and execution teams	Work conflicts, Delays, rework, cost overruns	4	4	16	i) Regular design-review meetings, ii) Early execution involvement iii) Clear communication protocols	1	4	4	Tolerable with Controls
1.2	**Identification of required resources and workforces**	Inadequate workforce planning	unsafe work practices, personal injury	3	4	12	i) Identification of required workforce and resources ii) Determine qualification, assessment and checks criteria for workforce and resources	1	4	4	Tolerable with Controls
		Over-reliance on untrained labour for critical tasks	High accident risk, reduced work efficiency	3	4	12	i) Competency certification, ii) Task-specific safety training, mentorship programs	1	4	4	Tolerable with Controls
1.3	**Obtain regulatory permit**	Delayed approval of environmental or safety permits	Project delays, financial losses	3	3	9	i) Pre-submission planning, ii) Dedicated compliance team iii) Proactive follow-ups	1	3	3	Tolerable As-is
		Non-compliance with local or national safety regulations	Legal penalties, project stoppages	3	3	9	i) Early engagement with regulatory authorities ii) Compliance audits iii) Permit-to-work system	1	3	3	Tolerable As-is

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1.4	**Site inspection and layout**	Undetected site hazards (e.g., unstable ground, underground utilities)	equipment damage, worker injuries	4	4	16	i) Geotechnical survey ii) underground utility mapping iii) Site hazard assessment	1	4	4	Tolerable with Controls
		Poor site access planning	Restricted movement of heavy machinery, increased accident risk	4	5	20	i) Clear site vehicle/equipment management plan ii) Designated walkways iii) Proper road surfacing	1	5	5	Tolerable with Controls
2.	**Civil Construction Activities**										
2.1	**Drilling for Pile**	Incompetent workforce,	Personal Injury	4	5	20	i) Trained & authorised operator and involved team ii) Adherence of permit to work system	1	5	5	Tolerable with Controls
		Underground utility strike- electrical, gas, water	Explosion, electrocution, flooding, fire	4	4	16	i) Utility survey ii) Underground cable/pipe detection iii) Work permit system compliance	1	4	4	Tolerable with Controls
		Collapse of borehole	Entrapment, injury to workers	3	4	12	i) Proper casing, ii) Ground stabilization, iii) Use of bentonite slurry	1	4	4	Tolerable with Controls
		Rotating and moving parts of drilling rig	Entanglement, amputation	4	3	12	i) Guarding of rotating parts, ii) Safe distance from rotating parts	1	3	3	Tolerable As-is
2.2	**Pile Load Test (Static, Dynamic and Lateral)**	Failure of jacking/loading equipment	Sudden collapse, injury, structural damage	4	4	16	i) Equipment inspection ii) load distribution assessment	1	4	4	Tolerable with Controls
		Falling load or displaced test components	Impact injuries, fatality	4	5	20	i) Use of barricades ii) Controlled access iii) Safe lifting compliance	1	5	5	Tolerable with Controls
2.3	**Excavation**	Cave-in or collapse	Burial, suffocation, fatality	4	5	20	i) Shoring, benching, sloping as per soil condition ii) Heavy Equipment restriction near excavation	1	5	5	Tolerable with Controls
		Contact with underground services	Electrocution, explosion, flooding	3	5	15	i) Utility detection survey, ii) Hand digging near utilities	1	5	5	Tolerable with Controls
		Water ingress leading to instability	Collapse, drowning risk	4	4	16	i) Proper dewatering arrangements ii) Monitoring of groundwater levels	1	4	4	Tolerable with Controls
2.4	**Shuttering works**	Formwork failure due to poor support	Structural Collapse, injury	3	5	15	i) Proper design and calculation of formworks ii) Pre-use inspection iii) Bracing reinforcement	1	5	5	Tolerable with Controls

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		Falling from height during erection	Fracture, head injury	4	4	16	i) secured work platforms ii) Use of fall protection	1	4	4	Tolerable with Controls
2.5	**Reinforcement**	Sharp edges of rebar	Cuts, punctures, infections	4	3	12	i) Covering exposed rebar ends ii) Use of cut resistant gloves	1	3	3	Tolerable As-is
		Heavy rebar lifting/handling	Musculoskeletal injuries, crush injuries	4	3	12	i) Mechanical lifting aids, ii) Team lifting	1	3	3	Tolerable As-is
2.6	**Concreting**	Concrete splash in eyes/skin contact	Chemical burns, eye injuries	4	3	12	i) Use of PPE (goggles, gloves) ii) Washing facility	1	3	3	Tolerable As-is
		Formwork collapse during pouring	Entrapment, crush injuries	3	4	12	i) Pre-inspection, ii) Controlled pouring sequence	1	4	4	Tolerable with Controls
2.7	**Masonry works**	Collapse of partially built wall	Impact injury, fatality	3	4	12	i) Temporary bracing, ii) Progressive construction sequence	1	4	4	Tolerable with Controls
		Dust exposure from mortar mixing cutting	Respiratory issues, lung diseases	4	2	8	i) Wet cutting, ii) Dust extraction, iii) Respiratory protection	2	2	4	Tolerable As-is
3.	**Mechanical Construction Activities**										
3.1	**Fabrication of cryogenic storage tanks**	Hot work (welding, cutting, grinding, gas cutting)	Fire, explosion, burns, exposure to toxic fumes	4	5	20	i) Trained fire watch deployment ii) Hot work permit compliance iii) Proper ventilation at workplace, iv) PPE (flame-resistant clothing, face shields, leather apron and gloves)	1	5	5	Tolerable with Controls
		Working at height (tank assembly, welding at elevated positions)	Falls from height, head injuries, fractures	4	4	16	i) Secure working platform ii) Full-body harness with double lanyard iii) lifeline system	1	4	4	Tolerable with Controls
		Scaffolding collapse due to improper erection	Falls, entrapment, severe injuries	3	5	15	i) Scaffolding design approval, ii) Load-bearing assessment iii) Competent scaffolding inspector approval	1	5	5	Tolerable with Controls
		Lifting of tank dome roof or other structural components	Load drop, structural failure, fatality	4	5	20	i) Pre-lift planning, ii) Certified rigging and lifting gear, iii) Ground stability assessment, iv) Trained and authorised personnel	1	5	5	Tolerable with Controls
3.2	**Lifting of compressor, turbine, air**	Incompetent or unauthorised workforce	Personal injury, property damage	4	5	20	i) Assessment of involved team ii) Validation of competency and authorization	1	5	5	Tolerable with Controls

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	purification unit, erection of distillation column- cold boxes and heat exchanger						iii) Work permit system compliance				
		Lifting operations at extreme heights	Load swing, struck-by incidents, falling objects	4	5	20	i) Crane selection based on weight and height, ii) Wind speed monitoring, iii) Tagline use iv) exclusion zones	1	5	5	Tolerable with Controls
		Overloading or misalignment of lifting equipment	Load drop, property damage, fatality	4	5	20	i) Pre-lift study, ii) crane selection based on load and height iii) engineered rigging plan iv) adherence to Permit to work system	1	5	5	Tolerable with Controls
		Sudden wind impact during lifting	Uncontrolled swinging, collision	4	5	20	i) Review of weather prior to lifting work ii) Wind speed monitoring, iii) wind speed determination for safe lifting and use of tag lines	1	5	5	Tolerable with Controls
		Ground instability under crane	Crane overturning, dropped load,	4	5	20	i) Soil compaction ii) Ground bearing capacity assessment iii) Use of outrigger mats for stability	1	5	5	Tolerable with Controls
3.3	**Piping fabrication and erection**	Hot work in confined spaces (welding, grinding, gas cutting)	Oxygen deficiency, fire, explosion risk	4	4	16	i) Confined space entry permit, ii) Atmospheric monitoring, iii) Emergency rescue plan, iv) Fire blanket use	1	4	4	Tolerable with Controls
		Improper pipe alignment and high-pressure testing	Pipeline rupture, leaks, explosion risk	3	4	12	i) Pipe stress analysis, ii) Controlled tightening sequence iii) Pressure relief systems iv) Hydrotesting safety measures	1	4	4	Tolerable with Controls
		Work at height for pipe rack installation	Falls from scaffolding, struck-by tools/materials	3	4	12	i) Edge protection ii) Tool lanyards iii) Secured platform, iv) Worker fall protection	1	4	4	Tolerable with Controls
		Welding defects in high-pressure lines	Leak, explosion	3	4	12	i) Qualified welders, ii) Radiographic testing as per design requirement iii) Hydrotesting as per design pressure	1	4	4	Tolerable with Controls
		Incorrect valve or flange installation	Process inefficiency, leakage	3	4	12	i) QA/QC inspection, ii) bolt torque verification, iii) correct gasket selection	1	4	4	Tolerable with Controls

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3.4	**Non-destructive testing (NDT)**	Radiation exposure from radiographic testing	Long-term health issues, radiation burns	4	3	12	i) Controlled radiation area ii) Radiation safety officer supervision, iii) Radiation warning signs iv) Dosimeter monitoring v) Radiation testing work permit	2	3	6	Tolerable with Controls
		Inadequate PPE or shielding for NDT operators	Increased radiation dose, long term health issues	3	4	12	i) Lead shielding barriers, ii) TLD (Thermoluminescent Dosimeter) badges iii) Periodic medical checks	1	4	4	Tolerable with Controls
3.5	**Corrosion protection and painting.**	Inhalation of toxic fumes from coatings	Respiratory illness, dizziness	3	3	9	i) Acknowledgement of safety data sheet ii) PPE (respirators) iii) proper ventilation or fume extraction system at workplace iv) worker rotation	1	3	3	Tolerable As-Is
		Flammable paint and solvents	Fire, property damage, personal injury	4	4	16	i) Controlled storage environment ii) Firefighting system readily available	1	4	4	Tolerable with Control
		Work at height for painting large structures	Falls, improper harness use, scaffolding failure	4	4	16	i) Certified scaffolding ii) full-body harness with lanyard, iii) Mobile elevated work platform use	1	4	4	Tolerable with Controls
3.6	**Thermal Insulation for Cryogenic Equipment- perlite filling, fiberglass and mineral wool insulation**	Insulation work at height (tanks, cold boxes, pipelines)	Falls, dropped tools/materials, heat stress	4	4	16	i) Fall protection systems, ii) Controlled material lifting, iii) Hydration plan for workers	1	4	4	Tolerable with Controls
		Perlite dust inhalation	Respiratory problems, skin irritation	3	2	6	i) Use of enclosed filling system ii) Dust extraction system and respirators	1	2	2	Tolerable As-is
		High temperature/heat exposure during use of furnace	Skin Burn, fire,	3	5	15	i) Pre use inspection of furnace ii) Entry restricted in vicinity iii) Firefighting equipment readily available	1	5	5	Tolerable with Controls
4.	**Electrical and Instrumentation (E&I) Works**										
4.1	**Power distribution system Installation- (132KV substation, Switchgear panels)**	Heavy lifting of transformers, switchgear panels	Load drop, property damage, injury, fatality	4	5	20	i) Pre-lift study, ii) Proper rigging/lifting plan iii) ground stability check, iv) adherence to PTW requirements	1	5	5	Tolerable with Controls
		Working at height for busbar and cable tray installation	Fall from height, serious injuries, fatality	4	4	16	i) Use of certified scaffolding, ii) Full-body harness, iii) Proper anchorage points	1	4	4	Tolerable with Controls

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		Manual handling of heavy panels	Musculoskeletal injuries, dropping hazards	4	3	12	i) Use of mechanical lifting aids ii) Team lifting techniques, iii) Proper ergonomic practices	1	3	3	Tolerable As-is
4.2	**Cable laying and termination**	Manual handling and ergonomic strain	Musculoskeletal injuries, fatigue	3	2	6	i) Proper cable pulling techniques ii) Mechanical aids, iii) Rotation of worker	1	2	2	Tolerable As-is
		Work at height (cable tray installation)	Personal injury due to fall of materials and personnel	4	4	16	Use of certified scaffolding, full-body harness, anchorage points	1	4	4	Tolerable with Controls
4.3	**Installation of lighting and earthing system**	Work at height for light fixtures installation	Falls from ladders, scaffolding failures, personal injury	4	4	16	i) Certified scaffolding ii) Use of mobile elevated work platforms iii) Proper PPE	1	4	4	Tolerable with Controls
		Improper earthing connection	Electrical faults, electrocution	3	4	12	i) Resistance testing ii) Compliance with IS standards iii) Verification before commissioning	1	4	4	Tolerable with Controls
4.4	**Automation and control panel installation (DCS & PLCs)**	Incorrect wiring and terminations	System malfunction, short circuit, fire	3	4	12	i) Functional checks ii) wiring inspection, iii) Adherence to P&ID drawings	1	4	4	Tolerable with Controls
		Exposure to electromagnetic interference (EMI)	Signal distortion, inaccurate readings	3	2	6	i) Shielded cables ii) Proper grounding iii) Separation of power and signal cables	1	2	2	Tolerable As-is
		Hot work near control panel	Fire, burn	4	4	16	i) Hot work permit ii) Fire watch iii) Use of fire-resistant blankets	1	4	4	Tolerable with Controls
4.5	**Instrumentation setup (flowmeter, pressure transmitters, temperature sensors and control valves)**	Pressurized fluid/gas leaks during installation	Permanent disability, personal injury	4	4	16	i) Leak test before commissioning ii) PPE (face shields, gloves) iii) Controlled depressurization	1	4	4	Tolerable with Controls
		Work at height for sensor/valve mounting	Falls, structural impact injuries	4	4	16	i) Fall protection measures ii) Scaffold access	1	4	4	Tolerable with Controls
		Incorrect instrument calibration	Process failure, equipment damage, safety interlock malfunction	3	4	12	i) Calibration by certified personnel ii) Reference instrument cross-checking	1	4	4	Tolerable with Controls
4.6	**E&I testing and calibration-loop**	Contact with live circuits	Shock, burns, fatality	4	4	16	i) LOTO procedure, ii) Circuit de-energization, iii) Use of insulated gloves and mats	1	4	4	Tolerable with Controls

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	checking, function testing and signal validation	High-voltage electrical exposure during live testing of energized panel	Electric shock, arc flash, severe burns, fatality	4	4	16	i) Permit-to-work system ii) LOTO (Lockout/Tagout) iii) Insulated tools and Arc flash suits iv) Approach barriers	1	4	4	Tolerable with Controls
		Cable short circuit during testing	Fire, electrocution, equipment damage	3	4	12	i) Proper insulation stripping ii) Phase identification iii) Megger testing before energization	1	4	4	Tolerable with Controls
		Handling of hazardous gases for calibration (e.g., N2, O2, Ar, CO2, CO)	Asphyxiation, explosion risk	3	4	12	i) Proper ventilation, ii) Gas detection systems, iii) Use of calibrated gas cylinders	1	4	4	Tolerable As-is
5.	**Plant Testing and Commissioning Activities**										
5.1	**Pressure testing and leak detection by hydrotesting (water pressure test) and pneumatic testing (air/nitrogen)**	Over-pressurization leading to pipe rupture	High-pressure explosion, flying debris, severe injury/fatality	4	5	20	i) Pressure relief valves ii) Stepwise pressure increase iii) Barricading the test area iv) Adherence of permit to work system	1	5	5	Tolerable with Controls
		Air/Nitrogen testing with improper venting	Asphyxiation, uncontrolled gas release	5	4	20	i) Controlled venting system, ii) Oxygen level monitoring, iii) Exclusion zones	1	4	4	Tolerable with Controls
		Hose or fitting failure under pressure lead to struck	Whipping hoses, personal injury	4	4	16	i) Standard high-pressure-rated hoses ii) Proper securing of connections iii) Visual inspection before testing	1	4	4	Tolerable with Controls
5.2	**Cleaning and flushing of pipelines**	High-pressure	Property damage, personal injuries	4	4	16	i) Proper pipe restraints ii) Controlled flushing velocity iii) Real-time monitoring	1	4	4	Tolerable with Controls
		Chemical exposure from cleaning agents	Skin burns, respiratory irritation	4	3	12	i) Use of compatible cleaning agents ii) PPE (gloves, respirators) iii) Proper disposal of chemicals	1	3	3	Tolerable As-is
		Wastewater disposal after flushing and cleaning	Environmental contamination, regulatory non-compliance	3	2	6	i) Wastewater collection and proper disposal system	1	2	2	Tolerable As-is
5.3	**Equipment function testing (compressor, turbine, control valves and**	Unexpected equipment startup	Entanglement, impact injuries, fatality	4	4	16	ii) LOTO (Lockout/Tagout) iii) Functional interlock checks iv) Remote startup notification, v) Two-way communication	1	4	4	Tolerable with Controls
		High-speed rotating	Mechanical failure, flying	4	4	16	i) Pre-startup mechanical integrity checks ii) Protective enclosures	1	4	4	Tolerable with Controls

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	process safety system calibration of instrument	equipment malfunction	debris, severe injuries, fatality				iii) Vibration monitoring				
		Leakages in process safety systems	Process deviation, fire, toxic exposure	4	5	20	i) System integrity check ii) Pressure monitoring iii) Automated emergency shutdown system	1	5	5	Tolerable with Controls
5.4	**Performance guarantee test**	Extreme operating conditions during performance validation	Equipment failure, thermal stress, explosion risk	4	5	20	i) Incremental load testing ii) Real-time performance monitoring iii) Redundant safety systems	1	5	5	Tolerable with Controls
		Unstable process conditions leading to sudden shutdown	Production loss, potential damage to system	3	4	12	i) Simulation-based risk assessment ii) Emergency bypass mechanisms iii) Trained operators	1	4	4	Tolerable with Controls
		Noise hazards from full-load testing	Hearing damage, fatigue	4	3	12	i) Noise level survey ii) use of ear muffs	1	3	3	Tolerable As-is
6.	**Project Handover and Documentation**										
6.1	**Handover of as-built drawings, manuals, and warranties, operational and maintenance procedures**	Errors or omissions in as-built documentation	Incorrect operation, potential equipment damage	3	4	12	i) Thorough documentation review ii) Cross-verification with site conditions, iii) Approval process from authority	1	4	4	Tolerable with Controls
		Incomplete or unclear maintenance procedures	Improper maintenance, increased failure risk, safety incidents	3	3	9	i) Detailed O&M (Operation & Maintenance) manual ii) Operator training, iii) Validation by the engineering team	1	3	3	Tolerable As-is
6.2	**Formal handover to the client or operations team**	Failure to communicate pending issues or punch list items	Operational inefficiencies, unresolved safety risks	3	3	9	Pre-handover inspection, structured punch list tracking, final walkthrough	1	3	3	Tolerable As-is
		Lack of operational readiness of plant personnel	Delayed response to emergencies, incorrect procedures followed	3	4	12	Simulation-based training, emergency response drills, process flow familiarization	1	4	4	Tolerable with Controls
		Incomplete transfer of warranties and service contracts	Delayed maintenance, disputes on equipment failures	3	3	9	Proper documentation handover, clear tracking of warranty periods, signed acknowledgment from the client	1	3	3	Tolerable As-is

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Table-5 presents a Hazard Identification and Risk Assessment (HIRA) for cryogenic air separation plant construction. There are six key phases of CASP construction project which are considered into this study, it classifies activities (civil, mechanical, electrical, etc.), identifies potential hazards, and assesses initial risks. Control measures like PPE, work permits, and training are implemented in order to mitigate the risks. Residual risk is reassessed after applying the controls to ensure safety. The table facilitates a structured approach toward the minimization of workplace hazards and the enhancement of safety adherence at the site.

6. Conclusion

This study outlines the need to fill the gaps in literature and industry practice by proposing an organized safety and risk management framework for the construction industry of CASP. It also suggests effective management of safety and risks associated with construction and commissioning by incorporating the STARR Model into the Safety Management System and using intricate step-by-step Hazard Identification and Risk Assessment processes. As a reaction to a shift in safety complexity, the important observations stress that the absence of a prescribed risk management approach in CASP projects has amplified safety problems, mainly during initial phase and the commissioning phase, which tends to be neglected. The HIRA design helps to ensures potential hazards are identified, assessed, and controlled at every stage, while the STARR Model ensures safety is integrated via recurrent training, evaluation, and enhancement. Such integration does not only improve hazardous conditions but also establishes safety culture and competency which reduces incidents occurrence. The adoption of a methodical and domain specific safety context can, as indicated by the study, significantly enhance CASP construction safety effectiveness, compliance, and construction productivity.

Despite the organized safety and risk management framework this study has some limitation. The proposed approach could not take into account the new safety and risk opportunities, and it was only applied to one practical CASP construction project. Risks in construction industry cannot be completely eliminated, the framework proposed, insists on continued monitoring and regular updating by the management to achieve effective implementation of safety measures and risk mitigation strategies. Moreover, this study can be further extended by considering other construction industries in India. In the long term, improving risk assessment models using modern sophisticated safety technologies will enhance the CASP construction industry's dependability and resilience while safeguarding its sustainability

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8. Declaration of Competing Interest

I hereby declare that the work submitted in this paper is entirely my own and has not been submitted in whole or in part for any other examination or qualification. This work is not a subject of any other course/program. Secondly, I declare that there do not exist any financial, personal or professional interests of mine which can, in any way, interfere with, or have interfered with, the objectivity or validity of the research. This statement carries my commitment to academic integrity and ethical principles in this paper.

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