TRANSPORT OF LIQUEFIED HYDROGEN: RISK ANALYSIS OF THE UNLOADING PROCESS AT THE SHIP TERMINAL

TRANSPORTE DE HIDRÓGENO LICUADO: ANÁLISIS DE RIESGOS EN EL PROCESO DE DESCARGA EN LA TERMINAL DE BUQUES

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WHY?

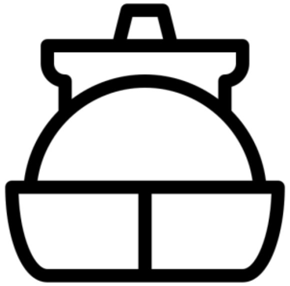
Environmental protection and the fight against climate change have driven the search for sustainable fuels, with hydrogen standing out as a promising alternative due to its high energy density and clean combustion. However, its **storage and transport present significant safety challenges, especially in its liquefied form (LH2), due to its low boiling temperature and low heat of vaporization**. Ensuring its safe use is key to its deployment in sectors such as energy and transport.

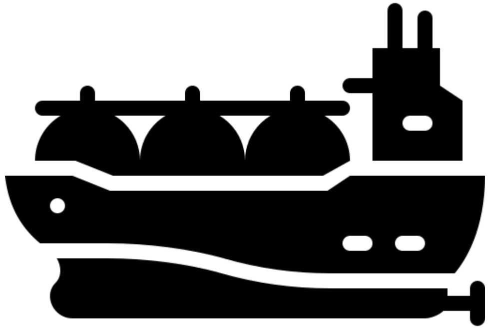
HOW?

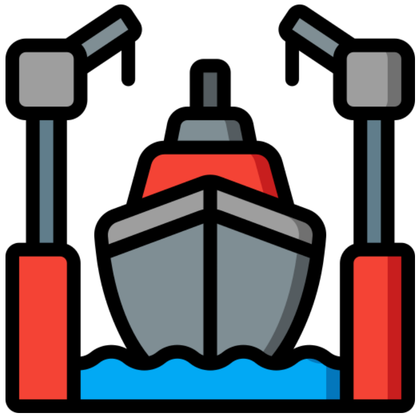
To **minimize the risks associated with hydrogen storage and transport**, risk analysis methodologies such as **HAZOP, HAZID and FMEA** are applied. These tools allow hazards to be identified, potential system failures to be assessed and preventive measures to be designed. Their implementation helps to optimize the safety and viability of hydrogen as an energy carrier, ensuring its sustainable and reliable development on a large scale.

Risk Assessment Methodologies

Risk Management is essential
Advanced safety protocols are key
Innovative research is crucial







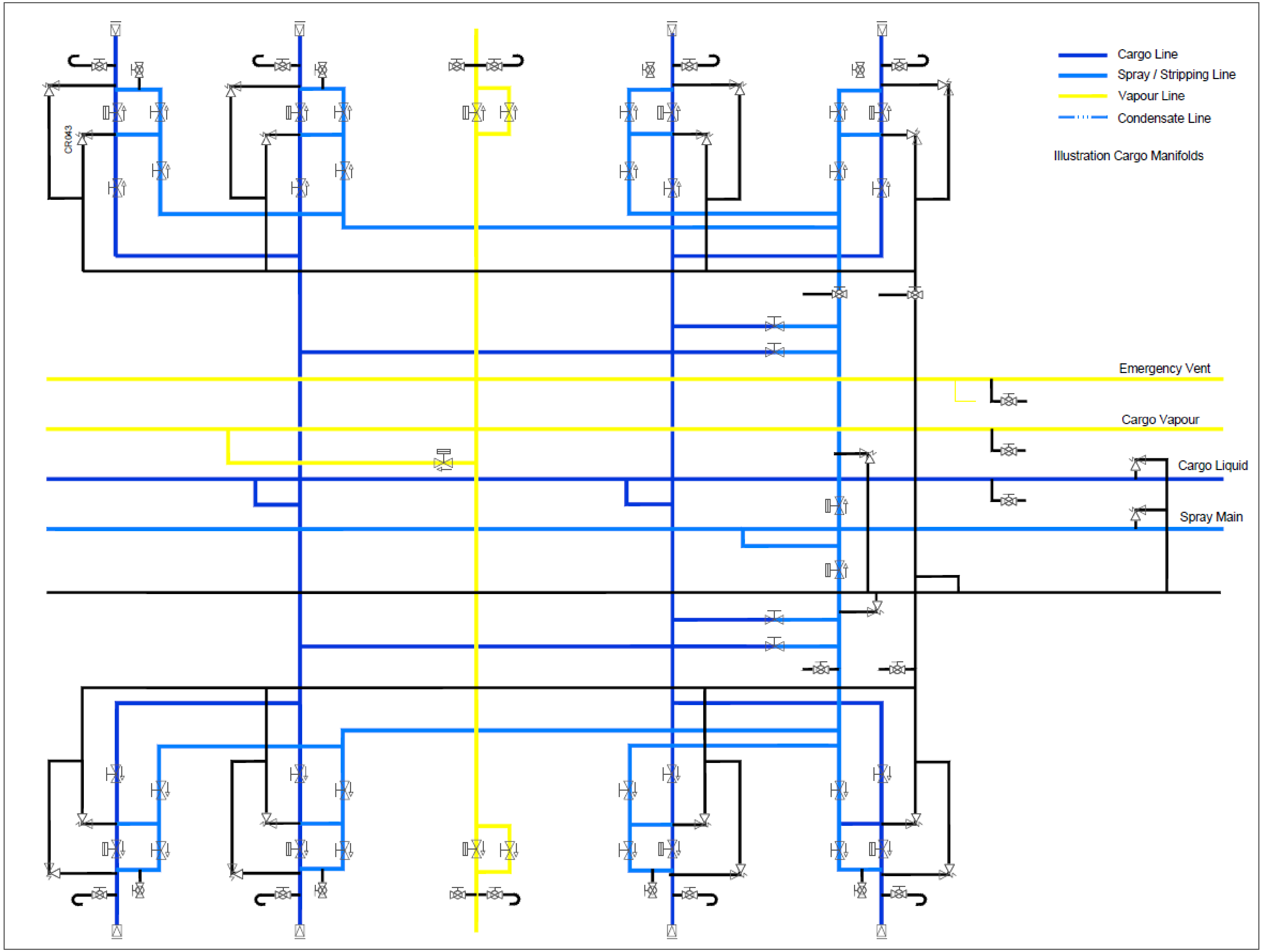
SHIP & TERMINAL

DESCRIPTION:

The vessel considered in this study is a Liquid Hydrogen Carrier (LHC) with a capacity of approximately **160,000 m^3** and an overall length of approximately **300 meters**. The LHC will transport the liquid at approximately -253ºC, atmospheric pressure and a ratio of liquid/gas volume of approximately 800 times.

This vessel is based on real vessels such as the Suiso Frontier as well as others that are in the project and design phase, although the size of the vessel is larger than those currently built, and it is a theoretical model that responds to a volume comparison of current LNG carriers.

SHIP & TERMINAL



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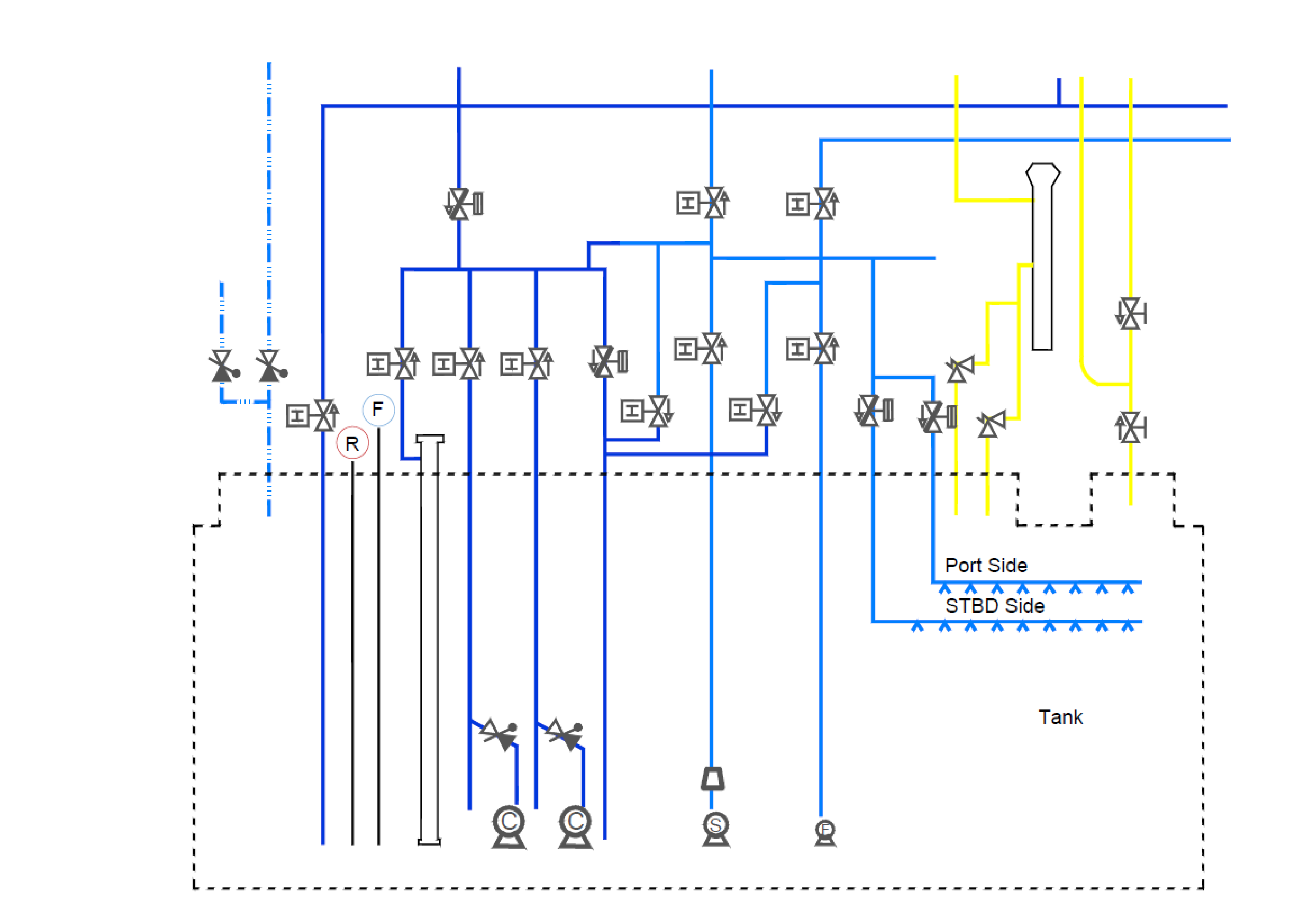


HAZOP

HAZOP METHODOLOGY

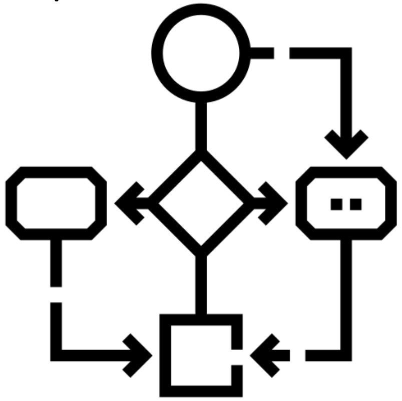
HAZOP

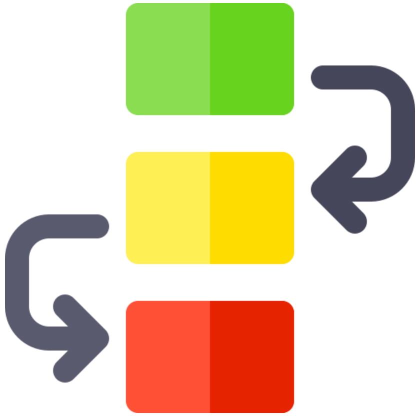
Hazard and Operability Study

Basic principles
- HAZOP concept
- Analysis structure

Applications
- Implementation in plant design
- Risk scenarios

Importance in risk assessment
- Prevention of operational failures
- Application in hydrogen transport





HAZID

HAZID METHODOLOGY

RISK CONCEPT

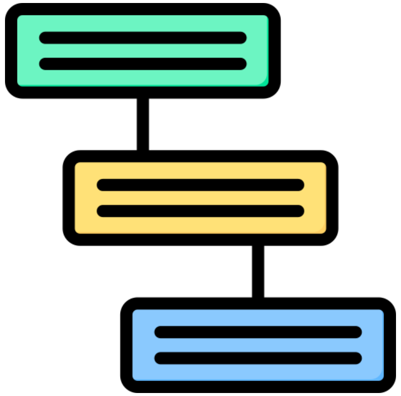
- **Hazard Identification (HAZID)**
  Identificación de Peligros (HAZID)
- **Results of HAZID analysis**
  Resultados del análisis HAZID
- **Need for Further Assessment**
  Necesidad de Evaluación Adicional
- **Application of HAZID Technique**
  Aplicación de la Técnica HAZID
- **Risk Definition**
  Definición de Riesgo
- **Risk Assessment of an Installation**
  Evaluación de Riesgo de una Instalación
- **Risk Analysis Methodologies**
  Metodologías de Análisis de Riesgos
- **Accident History Analysis**
  Análisis de Históricos de Accidentes

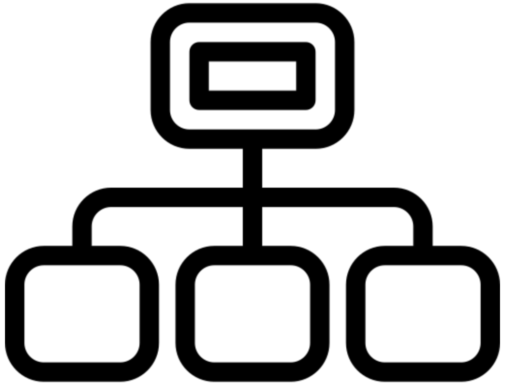
FMEA

FMEA METHODOLOGY

FMEA
Failure mode and effects analysis

- **FEMA applications**
  - Preliminary phase in failure analysis
  - Continuous improvement
- **Effects of failures**
  - Impact assessment
  - Identification of critical failures
- **Basic principles**
  - Definition and objectives
  - Levels of analysis
- **FMEA methodology**
  - Equipment and Systems Tabulation
  - Classification of failures





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HAZOP: Use Case

Case	Parameter word	Guide Word	Possible cause of deviation	Consequence	CONSEQUENCE	PROBABILITY	RISK
1	Flow in pipe LH2. Operation 1	NO	LH2 Spray Pump malfunction	No fluid circulation due to pump malfunction. No cool down of required lines.	1	3	3
2	Flow in pipe LH2. Operation 1	NO	Hydraulic Valves Failed to Open: Failed to open CS301	No fluid circulation due to hydraulic valves closed. No cool down of required lines.	1	2	2
3	Flow in pipe LH2. Operation 1	NO	Hydraulic Valves Failed to Open: Failed to open CS303	No fluid ci… to hydraulic… clos… ol down of required lines.	1	2	2
4	Flow in pipe LH2. Operation 1	NO	Hydraulic Valves Failed to Open… Failed to open CS071/072	…o fluid …ation in liquid crossover. No …own of required lines.	1	2	2
5	Flow in pipe LH2. Operation 1	NO	Hydraulic ESD Valves leak	…ossible creation of explosive atmosphere	5	3	15

Operator Intervention	Independent safeguards	Priority	Recommended action	Comments to recommended action	Mitigation / Contingency	CONSEQUENCE	PROBABILITY	RISK
Operator can see no fluid circulation & signal of pump running. Operator should control fluid recirculation to tank and try to restore spray pump availability or start another spray from other tank.	Control system will identify sequence failure or pump malfunction	Medium	Check Alarms of Spray Pump Pumps and piping systems (interconected) redundancy	P… …e system routing the ability to pump from the other 3 spray pu… …rough all the… …able to continue cooling the system and not gasify the l… …ssurize the li…	Contingency	0	3	0
Operator can see no fluid circulation & alarm no pressure or no flow at any section line.	Control system will identify sequence failure and send Trip Spray pump.	Medium	Check Hydraulic syste… Valves. Check autom… sequence.	…ot… …tional situation since it simply d… …e hydraulic valve at …discharg… …nded to emergency …p immediately to… …ulic valve that does not open …d to avoid a possible lea… …m the flange upstream of the CS301 …that does not open.	Mitigation / Contingency	0	1	0
Operator can see no fluid circulation & alarm no pressure or no flow at any section line.	Control system will identify sequence failure and first open CS300 to recirculate LH2 to tank, if opening valve CS300 failed then Trip Spray pump. The final safeguard is to open manually the CS304. Recirculation valve CL304 should be open during cooldown lines.	Low	C… …lic system & …eck automa… …ce.	…s not a serious operational situation since it simply does not open the hydraulic valve …discharge from the tank outlet line. First the recirculation through the CS300 line should be foreseen and if not a logical protection for not having circulation downstream of the hydraulic valve and the pump running, the pump should be commanded to emergency stop immediately and thus avoid an overpressure upstream of the hydraulic valve that does not open and avoid a possible leakage through the LH2 flange by the flange upstream of the CS301 valve that does not open.	Mitigation / Contingency	0	1	0
Operator can see no fluid circulation in crossovers lines	Automatically open CS300 to recirculate LH2 to tank to avoid overpressure in cross over lines	Medium	…c system & Hydraulics Va… …k automatic logic sequence.	This is not a serious operational situation since it simply does not open the hydraulic valve that distributes the LH2 to one side of the vessel or the other in the crossover. Provision should first be made for recirculation through the line from the CS300 to the tank and if recirculation to the tank is not possible and the pump running, the pump should be commanded to emergency shutdown immediately and thus avoid overpressure in the crossover and prevent a possible leak through any of the LH2 flanges provided.	Mitigation / Contingency	0	1	0
Operator can see alarm hazardous gas detection & close hydraulics valves CS071/CS072 to isolate te final section line prior to ESD Valve	Function logic that close CS071/CS072 if gas hazardous gas leak is detected	High	Isolate with manual valve this conection to shore	This is a high risk situation. To quantify the risk, it would be interesting to quantify the amount of gas that could escape through the internal leakage of the valve. It could be known by quantifying the amount of LH2 in the section considered coming from the previous cut-off valve and a simulation of gasification on deck from this valve. Provide safety distances to these risk points during operation. Provide for inspections and maintenance of critical valves.	Mitigation / Contingency	4	2	8

HAZOP: Example scenarios

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Node 1 field and record selection

CASE	POSSIBLE CAUSE OF THE DEVIATION	CONSEQUENCE	RISK
1. Flow rate in LH2 pipeline. Operation 1 - No flow	Leakage at flange or fitting	Possible creation of an explosive atmosphere.	15
2. Flow rate in LH2 pipe. Operation 1 - Excessive flow rate	LH2 pump malfunction	Excessive flow circulation. Process out of parameters	15
5. H2 steam pipe flow - Excessive flow rate	Overheating	Excessive vapour in the system, action should be necessary to liquefy the vapour or burn it off.	20

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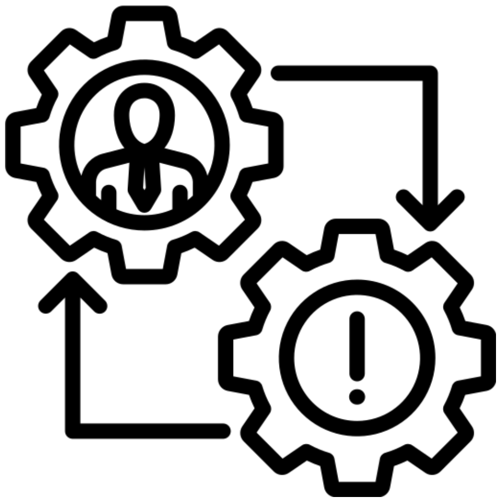
RESULTS: HAZOP RISK MATRIX

INITIAL		FREQUENCIES 1	2	3	4	5
SEVERITY	1	39	19	25	0	0
	2	12	13	15	0	0
	3	13	36	2	0	2
	4	0	11	5	0	0
	5	0	77	80	6	0

AFTER IMPROVEMENTS		FREQUENCIES 1	2	3	4	5
SEVERITY	1	63	15	9	3	0
	2	20	53	13	0	0
	3	6	11	2	0	0
	4	10	110	6	5	0
	5	24	5	0	0	0



TOTAL INITIAL	
Green	172
Yellow	95
Red	88

TOTAL AFTER	
Green	227
Yellow	123
Red	5

HAZID: Example scenarios

SCENARIO 1: DEVELOPMENT	CONSEQUENCES	RISK
Possibility of line breakage and supply hose breakage. Ship movement leading to leakage of LH2. Worst case scenario risk of fire or explosion.	Damage to persons. Damage to equipment or elements (possible cascading failures). Damage to the environment due to contamination.	15
SCENARIO 1: CONTROL MEASURES		
Limit of unloading operations according to port regulations. Breakaway system (ERS). Continuous monitoring by the ship. Periodic check of the mooring system (checklist).		8
SCENARIO 3: DEVELOPMENT	**CONSEQUENCES**	
Design line pressure between ESD valve and dry coupling exceeded due to loss of instrumentation air in the valves. Mechanical integrity at risk with LH2 leakage and possibility of fire or explosion.	Damage to persons. Damage to equipment or elements (possible cascading failures). Damage to the environment due to contamination.	20
SCENARIO 3: CONTROL MEASURES		
ESD warning on local panel. Operator must stop operation.		15

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RESULTS: HAZID RISK MATRIX

RISK = FREQUENCY x SEVERITY

	RISK MATRIX		FREQUENCIES				
			1	2	3	4	5
INITIAL MATRIX	SEVERITY	1	0	0	0	0	0
		2	0	0	1	2	11
		3	0	1	7	4	22
		4	0	2	4	2	3
		5	0	11	22	3	0

TOTALIZERS	
RED	52
YELLOW	41
GREEN	2

	RISK MATRIX		FREQUENCIES				
			1	2	3	4	5
MATRIX AFTER IMPROVEMENTS	SEVERITY	1	2	1	4	15	19
		2	1	15	3	5	2
		3	4	3	0	0	1
		4	15	5	0	0	0
		5	19	2	1	0	0

TOTALIZERS	
RED	2
YELLOW	14
GREEN	101

RESULTS

- **Risk Analysis for LH2 Unloading Operations**
- **Key Risks Identified**: Hydrogen leaks, ignition and explosion hazards, overpressure, cryogenic system failures, and atmospheric oxygen liquefaction.
- **Mitigation Measures**:
  - System segmentation with automatic valves and pressure relief systems.
  - Automation and control with interlocks and redundancy in sensors.
  - Overpressure management and evacuation circuits.
  - Continuous monitoring of the vacuum in cryogenic pipes.
- **Results**:
  - HAZOP: Reduced high-risk scenarios from 88 to 5.
  - HAZID: Reduced high-risk scenarios from 52 to 2.
  - FMEA: Qualitative failure identification.

CONCLUSIONS AND FUTURE LINES

- **Conclusions**:

  Enhanced safety through advanced leak detection, compartmentalization, and GCU redundancy.

  Further quantitative risk analysis, including the application of machine learning techniques, is needed for critical scenarios.

- **Future Lines**:

  New tools based on Artificial Intelligence, own developments.

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Thank you very much for your attention

- Muchas gracias por su atención -

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