HAZARD AND OPERABILITY STUDY (HAZOP AND BOW-TIE) IN CRYOGENIC AIR SEPARATION PROCESS PLANT

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ABSTRACT

Risk management is gaining more space in companies. The financial and human impacts arising from the absence or poor structuring of policies and actions for risk prevention are increasingly observed. In addition, economic losses for organizations and states due to remoteness and deaths are considerable. The chemical industry is a sector with high risks, thus presents itself with research problem for a better understanding of practices and opportunities for risk management assessment. Thus, this all proposes to apply risk assessment methodologies in a chemical industry in order to mitigate the dangers inherent to the process and its consequences. Exploratory bibliographic research was carried out in order to raise of the proposed theme, for the identification of a case study was carried out with process data. The results point to the need for the development of tools that allow the mapping of risks and are interactive. Another important point is the absence of similar tools, showing the importance of formalization participated and dissemination of risk management policy, as well as programs and systemic actions with this focus. The data show the importance of management, since the evaluation pointed out high risks in the operation, enabling recommendations to the process.

1. INTRODUCTION

Brazil is one of the countries with the most accidents at work, according to ANAMT, 2019, an each 48 seconds a work accident occurs and every 3 hours and 38 minutes a worker loses his life. These data place the country in fourth place in the world ranking, the most appalling is that more than 90% of accidents could be avoided if the measures of the regulatory standards of the Ministry of Labor were followed so that activities are carried out safely.

The chemical sector is one of the main ones in terms of work accidents. The data presented by the Statistical Yearbook of Accidents at Work (AEAT) of the PLANALTO, 2015 show that 5% of the total number of workers victims of accidents in 2014 were workers in the sector. Of the 35,487 accidents that occurred, 83.3% were typical accidents, 14.1% happened on the way, and 2.6% were caused by work-related illness. Of these, 11.3% were not registered, that is, they were occurrences without CAT (Communication of Occupational Accidents).

These data indicate the complexity of the chemical sector and the need for risk management tools [3]. One of the techniques used for risk analysis is HAZOP (Hazard and Operability), which celebrates its 60th anniversary in 2021, that is, a long-time helping management in any areas. This tool has shown good results

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in its application in industrial processes and activities. In addition to identifying the risks, it points out their causes and consequences, promoting actions before the accident happens (Meel et al., 2007; Palmer, 2004; Tyler, 2012). HAZOP aims to reduce and minimize risks and points out preventive and corrective measures for deviations identified in the area.

Studies with the methodology advanced at Imperial Chemical Industries, as a “critical examination” technique formulated in the mid-1960s, influenced by the increase in scale, and consequently, larger equipment that led to a significant increase in serious accidents. In 1974, Lawley published a disciplined procedure for identifying deviations from project intent, and the title of the work was “Operability studies and hazard analysis”. In this work, the necessary principles to carry out operability studies and risk analysis were defined due to the complexity of the new processes, the work defined the planning, execution and treatment of the operability study.

Kletz, 1999, talks about the importance of technique for the industry and for history, the author is one of the greatest admirers and promoters of HAZOP. This methodology has been adapted and applied in several areas, as it presents itself as a robust and structured technique [8]. To complete it, a fault tree will be developed, which consists of a deductive method that allows identifying the ways in which hazards can lead to accidents. Thus, it is intended to measure the real risk at each stage of the process, allowing the tool to search for unhealthy sectors that increase the risk of failures due to human factors.

According to Taylor, 2017, the best way to develop a HazOp is to mix automated techniques and manual approaches. As development time increases, the results get better. Humans are much better at holistic search than algorithms and at integrating different types of logic.

Another tool is the BOW-TIE analysis, as it is represented by a graph with this format. This is a schematic way of describing and analyzing risk pathways. The focus of this methodology is the barriers between causes and risk. The event to be studied is positioned in the center of the diagram, its causes on the left and its effects on the right, allowing the visualization of the relationships between the elements of the modeled system (Bleser, 2017).

2. BACKGROUND

HAZOP is a tool for identifying risks and hazards. It is a qualitative technique based on the use of guide words which question how the design intent or operating conditions may not be achieved at each stage of the design, process, procedure or system (Bleser, 2017). This tool is well accepted by companies.

The methodology for applying the HAZOP consists of the following steps:

A – The first step is to conceptually divide the process into distinct units. These units are the individual process equipment, such as a reactor, distillation column, pumps or tanks. It is not practical to apply a risk analysis methodology to all units, since initially those with lower risk can be discarded. This action aims to reduce time and cost, both for the development of the methodology and a company action plan [11].

B – Next, it is necessary to define a “node” or “point” (reactor, column, tank, valve).

C – In the third step, it is necessary to describe the role (function) of the “node” in the process.

D – Choose a process parameter that applies to the node: temperature, pressure, flow, level, concentration, pH, viscosity, volume, reaction, start, end, potency, inert.

E – Apply a guide word to the chosen parameter, this step aims to suggest probable deviations at this point. Table 1 shows the parameters, guide words and recurrent deviations most used in the chemical industry.

F – If the deviation is applicable, point out the possible causes and indicate which systems can protect the process.

G – Assess the probability and consequences of the deviation. Tables 2 and 3 show the levels of probability and severity of consequences, respectively. In addition, alphabetic (probability) and numerical (severity) indices are defined, which will facilitate the interpretation of results.

H – Recommend the action required for the event (what? through whom? when?)

I – Record the information.

J – Repeat steps F to I until all guide words have been applied to the selected parameter.

K – Repeat steps E to J for all parameters applicable to the selected node.

L – Repeat steps B to K with all points raised in the process.

Tab. 1 – Parameter, guide word and usual deviations in chemistry industry

Parameter	Guide word	Deviation
Temperature	More Less	High temperature Low temperature
Pressure	More Less	High pressure Low pressure
Flow	None More Less Inverse	No flow High flow Low flow Inverse flow
Composition	More	Presence of contaminants
Start/stop/maintenance	Other	Process

Applied from [12]

Tab. 2 – Probability levels

Index	Probability	Description
A	Frequent	It can always occur in the life of an item.
B	Probable	It will occur several times in an item's life.
C	Occasional	It may occur a few times in an item's life.
D	Remote	Unlikely, but possible to occur in the life of an item.
E	Improbable	Rare to occur, quite possibly not in the life of the item
F	Impossible	Unable to occur in an item's life.

Applied from [12]

Tab. 3 – Severity categories

Index	Description	Aspects
1	Catastrophic	It can result in one or more of the following events: death; total or permanent disability; irreversible environmental impact; minimum monetary loss of $10 million.
2	Critical	It can result in one or more of the following events: partial or permanent disability; occupational injuries or illnesses that could result in hospitalization; reversible environmental impact; monetary loss of $1 million or more and less than $10 million.
3	Marginal	It may result in one or more of the following events: occupational injury or illness resulting in one or more days of absence; reversible environmental impact; monetary loss of $100,000 or more and less than $1 million.
4	Negligible	It may result in one or more of the following events: occupational injury or illness not resulting in absence; minimal environmental impact; monetary loss of less than $100,000.

Applied from [12].

Once defined, the results will be analyzed based on the risk assessment matrix presented in Table 4, where the severity and probability mean the degree of a certain risk (eliminated, low, medium, serious, high).

Tab.4 – Risk assessment matriz

		Catastrofic (1)	Critical (2)	Marginal (3)	Negligible (4)
A	Frequent	High	High	Serious	Medium
B	Probable	High	High	Serious	Medium
C	Occasional	High	Serious	Medium	Low
D	Remote	Serious	Medium	Medium	Low
E	Improbable	Medium	Medium	Medium	Low
F	Eliminated	Eliminated			

The procedure above presents an interesting option for understanding the risks and dangers. HAZOP can be applied in various areas, such as an industrial wastewater treatment plant under construction. The tool enables the development of recommendations aimed at safety in operations. The study points out that, even though this study was carried out in a treatment plant, it can be developed for any industrial plant, at any stage of this life cycle: design, construction, operation, expansion and decommissioning [12].

The versatility of the tool is observed with its application in several segments, from companies that manufacture cement, radioactive industries and garbage collector cooperatives [13]–[15].

The use in the oil and gas industry also happens, in this case the method was applied with the aid of a computer, which allowed a better and more efficient evaluation. The authors claim that the tool is fundamental in work and process safety and provides better results in conjunction with computational tools such as multilevel modeling. The combination allows for a mix of risks related to people and processes [16].

These results show the versatility of the tool; however, it does not provide complete information for a risk analysis, especially in relation to all causes of deviations from the process parameters that are the main risk. The nodes of a process must be analyzed separately and interacting with the others (nodes), so a second tool is important for a complete risk feedback of an activity/process/work [17].

Using another tool allows for a better understanding of the process and associated risks. In this context, the BOW-TIE tool appears, which allows a different view of the risk. Its development is carried out considering the following steps:

1. Identification and representation of a specific risk as the central node of a BOW-TIE;
2. The causes of the event are listed considering the sources of danger;
3. The mechanism by which the source of danger leads to the critical event is identified;
4. Lines are drawn between the cause and the event, forming the left side of the BOW-TIE;
5. The barriers that would prevent each cause from leading to unintended consequences are made clear, these can be shown as vertical bars crossing the line;
6. On the right side of the BOW-TIE different potential consequences of risk are identified and lines drawn to radiate the risk event for each potential consequence;
7. Barriers to consequences are represented as bars that cross the radial lines;
8. Management functions that support controls (such as training and inspection) must also be shown under the BOW-TIE and linked to the respective control.

The method, like HAZOP, has varied applications and its advantage is to provide an image with a user-friendly interface that can be easily interpreted by non-experts, which allows the community to visualize the risks. In this case, the tool was used in natural gas transmission lines and the results enabled the identification of deficiencies and the management action necessary to block them, this is an advantage since, normally, this cannot be obtained through other methods of risk analysis (Muniz et al., 2017).

BOW-TIE diagrams must always be revised and updated if there are changes in the process, such as: new threats, consequences or degradation factors, changes in operation. Its use has grown a lot in an offshore environment, the results indicate the need to strengthen the link between risk assessment methodologies and decisions, allowing for a better understanding of the process and greater efficiency in decision making [19].

The automatic construction of these diagrams was proposed by Badreddine & Amor, 2013, based in Bayesian network. The authors claim that each scenario includes differences in their construction. Introducing a faster and more systematic methodology for Bow-Tie development.

Both methodologies have already been evaluated together to assess corrosion on oil platforms. The assessment allowed for low-cost recommendations, which involved changes in replanning activities and control of procedures and routines (Bleser, 2017). These works show the potential of both tools and their working together allows for the optimization of the assessment.

Thus, this work will aim to develop the methodologies of HAZOP and BOW-TIE together. The study will be carried out in a chemical industry, evaluating which information allows for the indication of risks or that increases the probability of accidents.

Air is a mixture of gases consisting primarily of nitrogen (78%), oxygen (21%), inert gas argon (0.9%). The rest of the mixture (0.1%) is made up mostly of carbon dioxide and the inert gases neon, helium, krypton and xenon. Air can be separated into its components using special distillation equipment. Air is commonly modeled as a uniform gas (no variation or fluctuation).

Dry air is relatively uniform in composition, with its primary constituents shown below. Ambient air may have around 5 vol% water concentration and may contain traces of other gases that are removed at one or more points in the air separation and purification system.

The two predominant components in dry air are oxygen and nitrogen. Oxygen has 16 a.u.a. and 14 a.u.u. Since these elements are diatomic in air, O_2 and N_2, the molar mass of oxygen is 32 kg/kmol and nitrogen 28 kg/kmol [21].

The main components of air (nitrogen, oxygen and argon) can be liquefied when subjected to low temperatures, on the order of -194.5 ºC at atmospheric pressure. Such temperatures are commonly used in low temperature air separation installations. Table 5 shows the condensing temperatures of air and its main components with their respective concentrations at atmospheric pressure.

Tab. 5 – Condensation temperatures of air and its main components with their respective concentrations at atmospheric pressure.

Compound	Temperature (°C)	Concentration (ppm)
Air	-194.5	-
Nitrogen	-195.8	-
Oxygen	-183.0	-
Argon	-185.7	-
Carbon Dioxide	-	300
Water	-	1000 - 10000
Organic		0 - 5

Source: ASPEN/HYSYS, 2016.

For air, as with other gases and vapors, the condensing (liquefaction) temperature increases with increasing pressure. However, it is necessary to reduce the air temperature below a defined temperature, which is the critical temperature, before liquefaction. The separation of the components of a liquid mixture can be achieved by vaporizing the mixture, where the more volatile components are separated from the others. Similarly, due to differences in the boiling points of nitrogen, oxygen and argon, separation by distillation is possible. Air separation can be performed in normal gases and the descending liquid is guaranteed by the presence of plates designed and built especially for this purpose (Fu et al., 2014).

The refrigeration needed to cool the air below the critical temperature is achieved by expanding the compressed gas, which in this case is nitrogen. This is an application of the general principle that a gas being compressed is heated, and conversely, that when a gas under pressure is expanded, then it is cooled.

2.1 Air Separation Technologies

Air separation plants are designed to generate oxygen and argon from the air through the processes of air compression, cooling, liquefaction and distillation. Air is separated to produce oxygen, nitrogen, argon and, in some special cases, other rare gases such as: krypton, xenon, helium and neon; through the cryogenic rectification of air. The products are generated in gaseous form for routing in pipelines or in liquid form for storage and distribution by trucks (Zhu et al., 2011).

Air can be separated into its components by distilling it into special units. Plants called air fractionation plants employ a thermal process known as cryogenic rectification to separate the individual components from one another to produce ultrapure nitrogen, oxygen and argon in liquid and gaseous forms.

The cryogenic air separation process is one of the most popular air separation processes, frequently used in medium and large industrial plants. This is the preferred technology for producing nitrogen, oxygen, and argon as gaseous and/or liquid products and is considered the most economically viable technology for plants with high production rates. In the current market scenario, all liquefied industrial gas production plants use cryogenic technology to produce liquid products (Smith & Klosek, 2001).

There are different variations that emerge from differences in user requirements in cryogenic air separation cycles for industrial gas production. The processing cycle depends on:

• How many products are required (only oxygen or nitrogen, oxygen and nitrogen or nitrogen, oxygen and argon);

• Required purity of products;

• Pressure of gaseous products;

• Which products need to be stored in liquid form.

In gas cryogenic processing various equipment's are used, such as distillation columns, heat exchangers, interconnection of cold streams, etc., which operate at very low temperatures, requiring adequate insulation. These items are located inside closed "cold boxes" or "cold boxes". Cold boxes are elevated structures with a circular or rectangular cross section. Depending on the type of plant, size and capacity, cold boxes can have a height of 15 to 60 m and 2 to 4 meters in diameter (Matragrano et al., 2016).

2.2 Case study

The analyzed plant belongs to a steel company and has the objective of producing liquid and gaseous oxygen. It was built in 1971. Figure 1 shows the flowchart of the oxygen factory. The flowchart was created in Microsoft VISIO ® software and contains only the equipment that is considered relevant in terms of simulation. The nomenclature of the chains does not correspond to the nomenclature given by the manufacturer, due to the difficulty in compiling all the information from the P&ID provided and due to the interest in establishing a common and easily decipherable nomenclature for all plants.

2.3 Process description

Atmospheric air (A01), after being filtered to remove particulates, enters compressor C201 where its pressure is increased to 5.7 kgf/cm²G (A02). The outlet temperature (A03) is adjusted to 42 °C with the aid of an after cooler. It then proceeds to the V101 separator drain to remove moisture. The output current (A04) goes to the H011~H036 heat exchanger battery, made up of 3 blocks, each containing 6 heat exchanger cores. As the air cools, moisture and CO2 solidify inside the equipment. For its removal, the equipment has an inversion valve system, where the passage of air and residual nitrogen alternates.

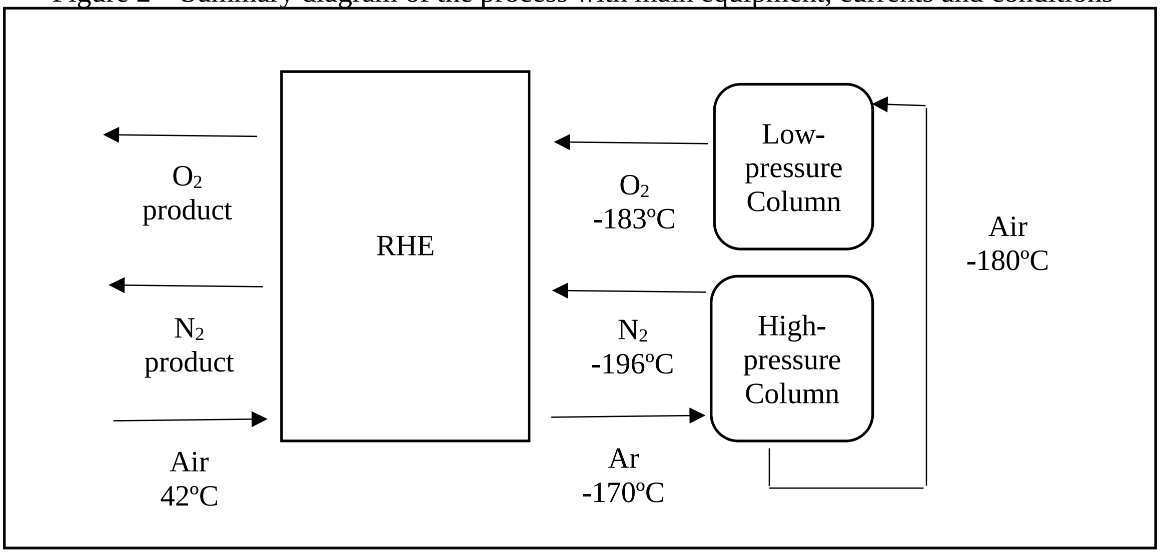
After passing through the heat exchangers, the air stream (A05), at -170 ºC, goes to the high-pressure column (T002). A residual current (W04) is also fed into it, coming from the column itself (current W01), used to heat the product O2 in a liquefier (H008). The number of stages and the profile of column pressures and temperatures on the FOX-T1200 are unknown. The bottom product (A06) is divided into two streams (A06-A and A06-B), which pass through silica gel absorbers (V002-A and V002-B) to remove impurities such as acetylene and hydrocarbons. These absorbers are followed by filters for removing silica dust. The output currents from the absorbers (A06-C and A06-D) mix (A06-E) and go to the upper column. At the top of the high-pressure column, the product nitrogen (N05), gaseous (-196 ºC), is removed within the specifications and goes to the H011~H036 heat exchanger battery where it heats up and reaches its final condition (N06). The column also has two lateral removals of residual nitrogen (W01 and W05), which will be used in energy integration at other points in the process. The column is for dishes and the feed/removal stages of products are ignored.

Before entering the upper column, the air stream (A06-E) is again cooled in a sub cooler (H007-A~C), composed of three heat exchangers, whose configuration is unknown. In them, the air stream exchanges heat with a stream rich in nitrogen (N03), also coming from the high-pressure column, and with three residual nitrogen streams (W03, W07 and W01-A), coming from the high and low-pressure columns.

In the low-pressure column (T011), the air (A07) richer in oxygen (-180 °C), is fed in an intermediate stage. The nitrogen current (N04) and residual nitrogen (W02) coming from the sub cooler are fed near the top, where the residual current (W06) is also removed, which will be used for cooling in the sub cooler. The oxygen leaving the reboiler (O01) passes through a successful filter absorber (V003) to remove impurities and returns to the column (O02). Also, at the bottom, the product oxygen (O03), liquid (-183 ºC), already within the specifications, is removed. This first passes through a liquefier (H008), where it is heated by part of the residual nitrogen stream coming from the high-pressure column (W01-B), which liquefies. Then, it goes in gaseous form (O04) to the H011~H036 heat exchanger battery, from where it leaves in the final condition (O05). The low-pressure column reboilers (V001) is a horizontal cylinder made up of two blocks, each containing six heat exchange cores. It also acts as a high-pressure column condenser.

The residual nitrogen stream leaving the sub cooler after heating (W08) goes to the H011~H036 heat exchanger battery, where it is heated again. Part of it is discarded (W09), in the process of dragging CO2 and moisture deposited inside the equipment. The other residual current (W05) goes to one of the two turbines (T001), which will reduce the pressure, aiming at additional cooling. The current coming from this system (W10) is added to the current coming from the top of the low-pressure column (W06) before it is taken to the sub cooler (W07). The energy generated in this equipment could be reused in the plant. However, as far as we have information, there is no reuse system installed. A summary of the process is shown in figure 2. The streams (air, oxygen and nitrogen) and main equipment (RHE and columns) are located inside the cold box.

Figure 2 – Summary diagram of the process with main equipment, currents and conditions

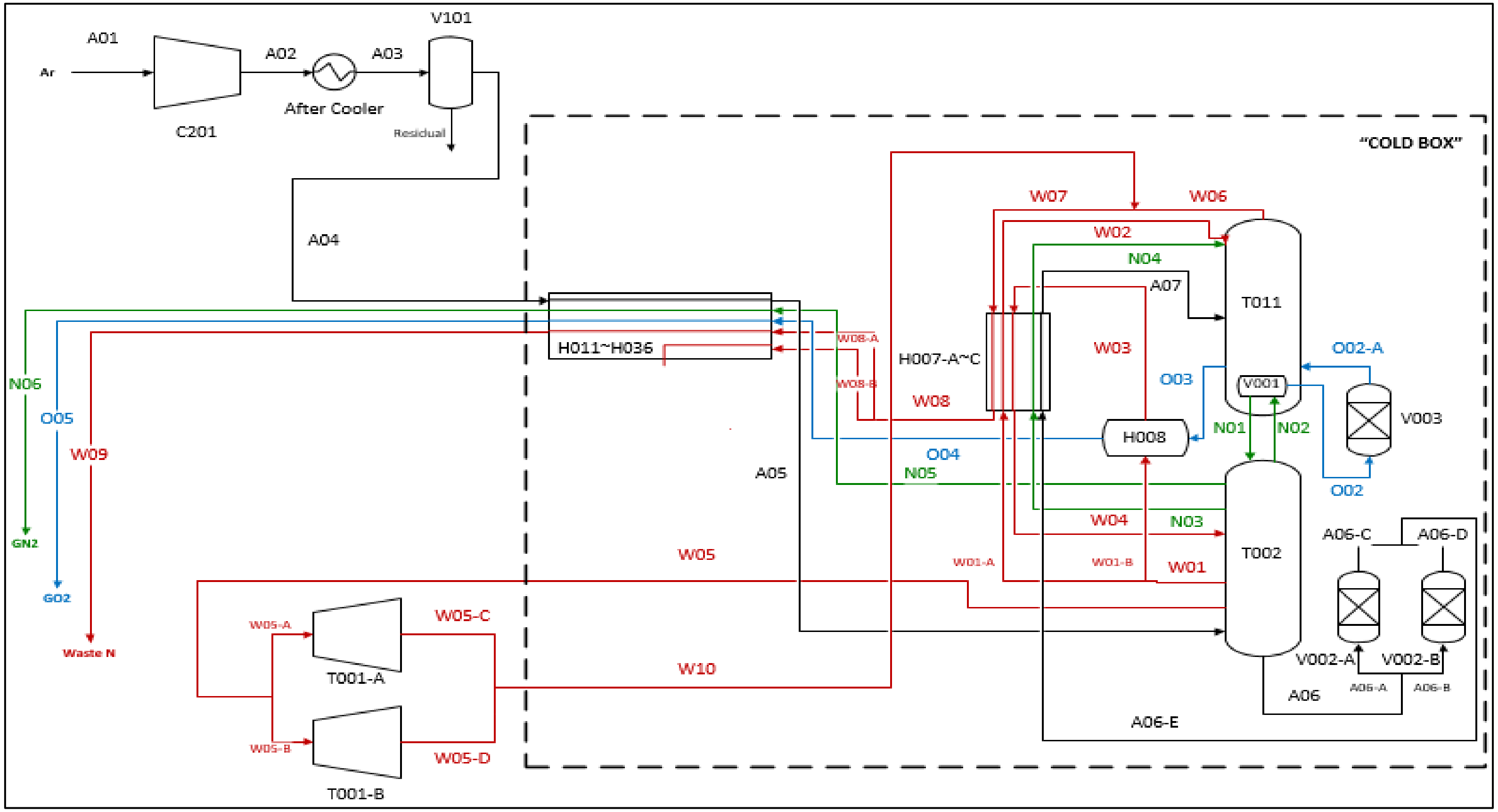


2.4 Choice of nodes

The reason for choosing the nodes will be the greater number of parameters involved in the process stage, the complexity of operations and the risk of accident in case of failure. The first node chosen was the RHE (H011-H036), which has 6 input currents and 6 output currents, only for this plant, that is, the equipment is shared by 2 other plants, but this data will not be considered. This equipment is extremely important for the process, as it removes CO2 and moisture, products that can cause problems if they enter the column.

The second node includes important components to the process, the separation columns. These equipment's work at low temperatures and are where the components are separated. It was decided to include both equipment due to lack of information (number of plates and exit locations), which would make HAZOP repetitive. Thus, considering both equipment, it is possible to have a better view of the risks inherent to both since they are linked processes, so any minimal interference triggers actions that can compromise the process. In Figure 3, an illustrative scheme of the nodes with all equipment and currents involved is presented. Once defined, the HAZOP was elaborated as mentioned above.

Fig. 1 – Process flowchart of the evaluated plant.



Legend (chains):

AXX = air currents; NXX = nitrogen streams; OXX = oxygen currents; WXX = residual nitrogen streams (waste)

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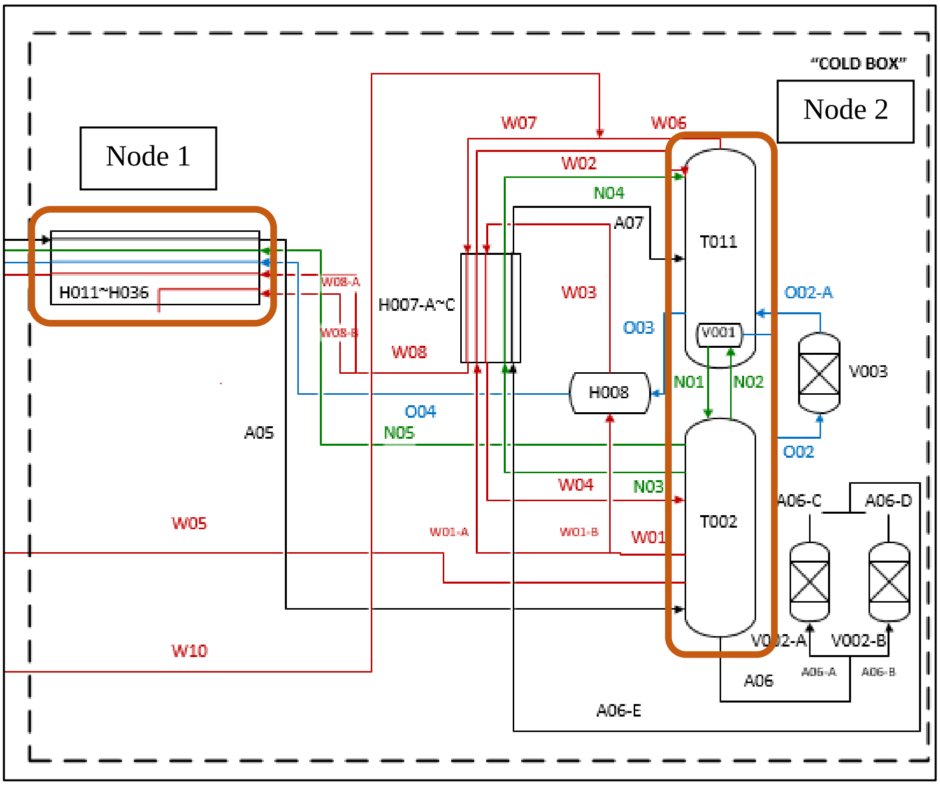
Figure 3 – Nodes chosen for HAZOP development



3 DISCUSSION

Table 6 shows the results obtained with HAZOP for the RHE (node 1). The results point to high pressure and the absence of flow as high risks for the process. Comments were included in the observations and questions were asked, which will be answered in the sequence of the work. As it is a plant in operation, the observations will be made with questions related to risk, with the objective of creating a questionnaire for a better understanding of the process and global analysis of the data. High temperature and high flow are considered serious deviations, the first would have more impact on the process, as it requires low temperatures for success. The second is related to process and work, as it could cause the equipment to rupture, putting employees in danger, as would happen with high pressure and lack of flow (high risk). The others were considered medium, low or non-existent risks. In Table 7 the HAZOP of the columns is presented, high pressure and lack of flow are also considered serious risks, however it is more likely to occur.

In both nodes there were two parameters considered high risk, high pressure and no flow.

The first two developed were at the RHE, the results are shown in Figures 4 and 5. High pressure can occur due to high process flow, or failure in valves or controller. In this case, the risk barriers that can avoid the danger are:

• sensor/alarm, which will notify the operator of the problem and allow his intervention;

• perception of the operator, who will be able to act and deal with the problem;

• drain, which acts by reducing pressure when it reaches a value above the set value.

If the deviation occurs, the palliative measures are:

• operation reduction, allowing the problem to be corrected and the operation resumed;

• product disposal, which enables line depressurization and pressure adjustment;

• process stop, if the actions are not enough, the process needs to be stopped and the necessary adjustments must be made;

If preventive and palliative measures are not enough, the process can be impacted, with loss of purity, a very important parameter to the process or equipment rupture, which would be catastrophic for the plant.

The absence of flow can occur through three faults (equipment, valve and controller), the event can be avoided through the action of sensor/alarm, indicator and operator. If the measures fail, it is necessary to dispose of the product, stop the process, reduce the operation or trigger the recovery protocol. If all measures described fail, there is the possibility of clogging of the column and loss of purity of the final product.

Table 6– HAZOP by RHE

	Hazard and Operability Analysis								
	System	RHE							
Item	Parameter	Guideword	Deviation	Cause	Consequences	Frequency	Severity	Risk	Observations
1	Temperature	More	Higher temperature	Equipment overload	Passage of contaminants	C	2	Serious	Is there a sensor and alarm on the RHE?
				Input current without flow	Current passage with different temperature for the process sequence				In case of elevation, there are procedures for quick action
				Exchange current at different temperature	Loss of purity due to contaminants solubilization				Controller maintenance protocol
				Controller failure					Acting protocol?
2		Less	Lower temperature	Equipment failure	Equipment clogging	D	3	Medium	Is there a sensor and an alarm?
				Input current without flow	Equipment breakage				Reversible valve maintenance
				Exchange current at different temperature					Protocol for the protection of employees?
				Controller failure					

3	Pressure	More	More pressure	high flow	Equipment break	C	1	High	Is there a sensor and an alarm?
				Valve closure or failure	Equipment overpressure				Action protocol for occurrence?
				Flow controller failure	Impact on the line and on the process				Equipment signal evaluation protocol?
					Loss of purity				Is there a relief or drain valve?
									Protocol for the protection of employees?
4		Less	Less pressure	Low or no flow	Product delivery out of specification	D	4	Low	Is there a sensor and an alarm?
				inverse flow	Loss of purity				Is there a protocol for action?
				Flow controller failure					
5	Flow	More	More Flow	Inlet valve breakage and closing	Overflow	C	2	Serious	Is there a sensor and an alarm?
				Controller failure and increased output flow	Loss of purity due to excess contaminants				Protocol for valve failure?
				Failure to send the signal to the control desk	High level and pressure in the high pressure column				Equipment signal evaluation protocol?
									Protocol for the protection of employees?
									Is there a drain to depressurize the line?

6		Less	Less Flow	Outlet valve breakage and closing	Uncontrolled temperature	C	3	Medium	Is there a sensor and an alarm?
				Falha no controlador e aumento da vazão de entrada	Loss of purity				Protocol for valve failure?
					Low level and pressure in high pressure column				Equipment signal evaluation protocol?
7		None	No Flow	Outlet valve breakage and closing	No flow	C	1	High	Is there a sensor and alarm for lack of flow?
				Controller failure and flow interruption	High column pressure loss				Protocol for valve failure?
				Equipment failure	Loss of purity				Equipment signal evaluation protocol?
				Failure to send the signal to the control desk	Clogging of the spine and rupture				Protocol for the protection of employees?
8		Reverse	Reverse Flow	Valve blocked	Loss of purity	C	3	Medium	Is there a reverse flow sensor and alarm?
				Manual or drain valve open	Return of components to column				Is there a sensor for pressure variation or product purity?
				Clogged passage	Pressure increase				Protocol for flow reversal?

				Controller failure	Loss of outlet pressure				
9	Composition	More	More Contaminants	Controller failure	Reduced process efficiency	D	4	Low	Is there a sensor and alarm for composition?
				Mixing of currents					Is there a drain to depressurize the line?
									Is there a protocol for action?
10	Deviation at departure	Other	Process			F	4	Eliminated	Is there a protocol for action?
11	Detour at stop	Other	Process			F	4	Eliminated	Is there a protocol for action?
12	Deviation in maintenance	Other	Process			F	4	Eliminated	Is there a protocol for action?

Table 7 – HAZOP by columns

	Hazard and Operability Analysis								
	System	Columns							
Item	Parameter	Guideword	Deviation	Cause	Consequences	Frequency	Severity	Risk	Observations
1	Temperature	More	Higher temperature	High temperature variation	Mechanical failure	C	2	Serious	Is there a sensor and alarm inside the column?
					Pipe thermal stress and possible rupture				Is there a sensor and alarm outside the column?

					Cryogenic liquid leak				Protocol for the protection of employees?
					Cold box break				Acting protocol?
2		Less	Lower temperature	-	-	F	1	Eliminated	
3	Pressure	More	More pressure	Line-to-column valve closed	Lack of flow for low pressure column	B	1	High	Pressure indicator and alarm?
				Flow controller failure	loss of purity				Automatic relief valve?
				Automatic relief valve closed or with problem	High pressure and possible rupture of the column				Rupture disk?
									Protocol for the protection of employees?
					Low level in low pressure column				Acting protocol?
4		Less	Less pressure	Locked and open high column pressure relief valve (pressure loss and return)	loss of purity	D	4	Low	Pressure gauge?
				Valve (drain or manual) open	Low level in low pressure column				Pressure alarm?
				Flow controller failure					Acting protocol?
5	Flow	More	More Flow	Line valve between	loss of purity	D	3	Medium	Is there a flow indicator and alarm?

				columns locked and open					
				Controller failure	High level in low pressure column				Purity indicator?
					Pressure loss in low pressure column				Pressure indicator and alarm?
									Acting protocol?
6		Less	Less Flow	Line-to-column valve partially closed	Absence of flow to upper column	D	2	Medium	Flow sensor and alarm?
				Controller failure	loss of purity				Flow controller?
					Low level in low pressure column				Equipment signal evaluation protocol?
									Acting protocol?
7		None	No Flow	Inlet valve closed	Lack of flow for low pressure column	B	2	High	Flow sensor and alarm
				Pressure loss between columns	loss of purity				Pressure sensor and alarm?
				Controller failure	Low level in low pressure column				Flow controller?
									Protocol for acting?
8		Reverse	Reverse Flow	Locked and open high column pressure relief valve (pressure loss and return)	loss of purity	C	2	Serious	Flow sensor and alarm
				Valve (drain or manual) open	Low level in low pressure column				Pressure indicator and alarm?

					Column temperature imbalance				Purity indicator?
					High flow at N_2 outlet				Flow and level indicator at N_2 output
					High level of N_2 in the tank				Protocol for acting?
9	Composition	More	More Contaminants					Low	
									Acting protocol?
10	Deviation at departure	Other	Process			F	4	Eliminated	Is there a protocol for action?
11	Detour at stop	Other	Process			F	4	Eliminated	Is there a protocol for action?
12	Deviation in maintenance	Other	Process			F	4	Eliminated	Is there a protocol for action?

For columns, high pressure can occur by:
• closing of the line valve between columns, which can be corrected by activating a sensor/alarm or operator perception for further intervention;
• failure in the flow controller, identified by the operator or bypassed by the relief valve, which will automatically reduce pressure;
• failure of the automatic relief valve, perceived by sensor/alarm and corrected by rupture disk actuation.

If there are failures in the predictive measures, it is necessary to activate the recovery protocol, discard the product, reduce the operation or stop the process. If both predictive and palliative measures fail, the process may experience loss of purity, low-pressure column level drop (from above), or column ruptures. The results for high pressure and no flow are shown in figures 6 and 7, respectively.

The absence of flow in the columns can be caused by:
• closing of the inlet valve, which can be corrected by activating the sensor/alarm and operator perception;
• controller failure, minimized by operator interference;
• pressure relief between columns, perceived by sensor/alarm triggering.

If this happens, palliative actions are triggering the recovery protocol, disposing of the product, reducing the operation or stopping the process. All these measures prevent the loss of purity, an important parameter for the process, absence of flow or low level in the low-pressure column, impacting the operation.

Figure 4 – BOW-TIE applied to "high pressure" risk in the RHE

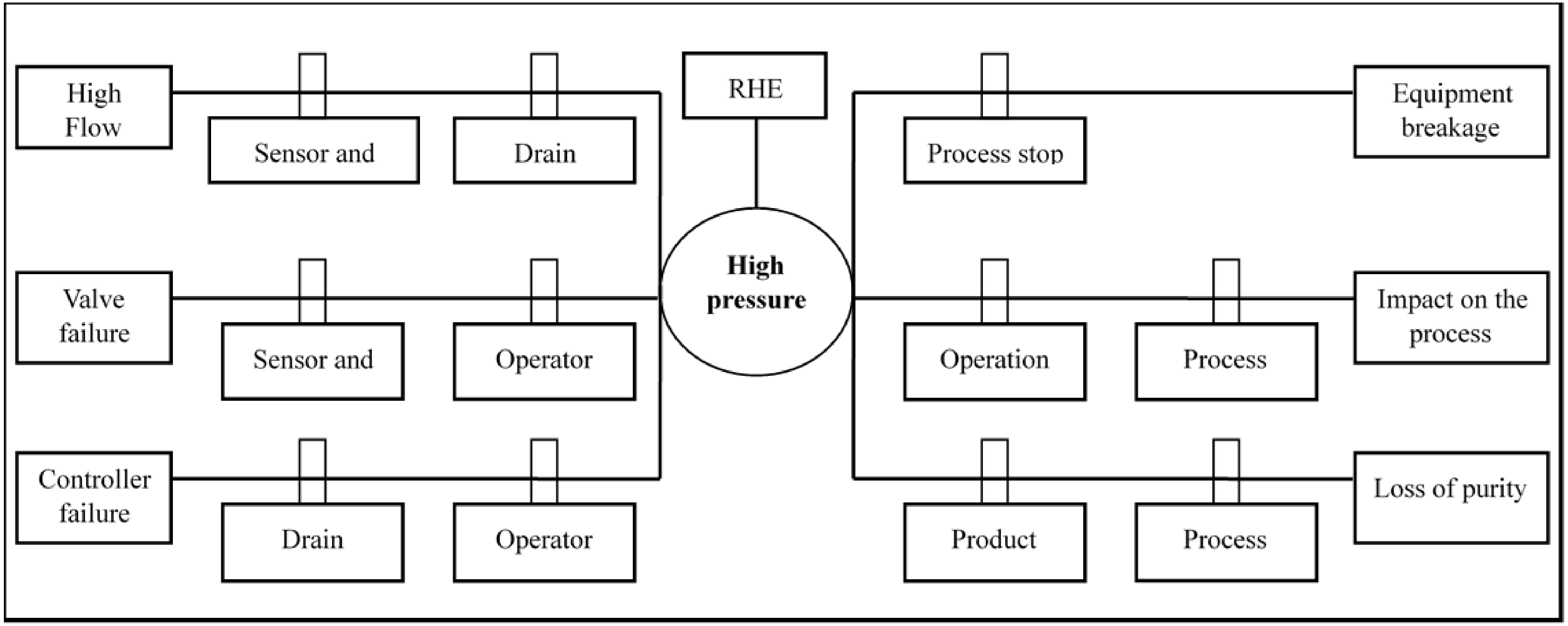


Figure 5 – BOW-TIE applied to "no flow" risk in the RHE

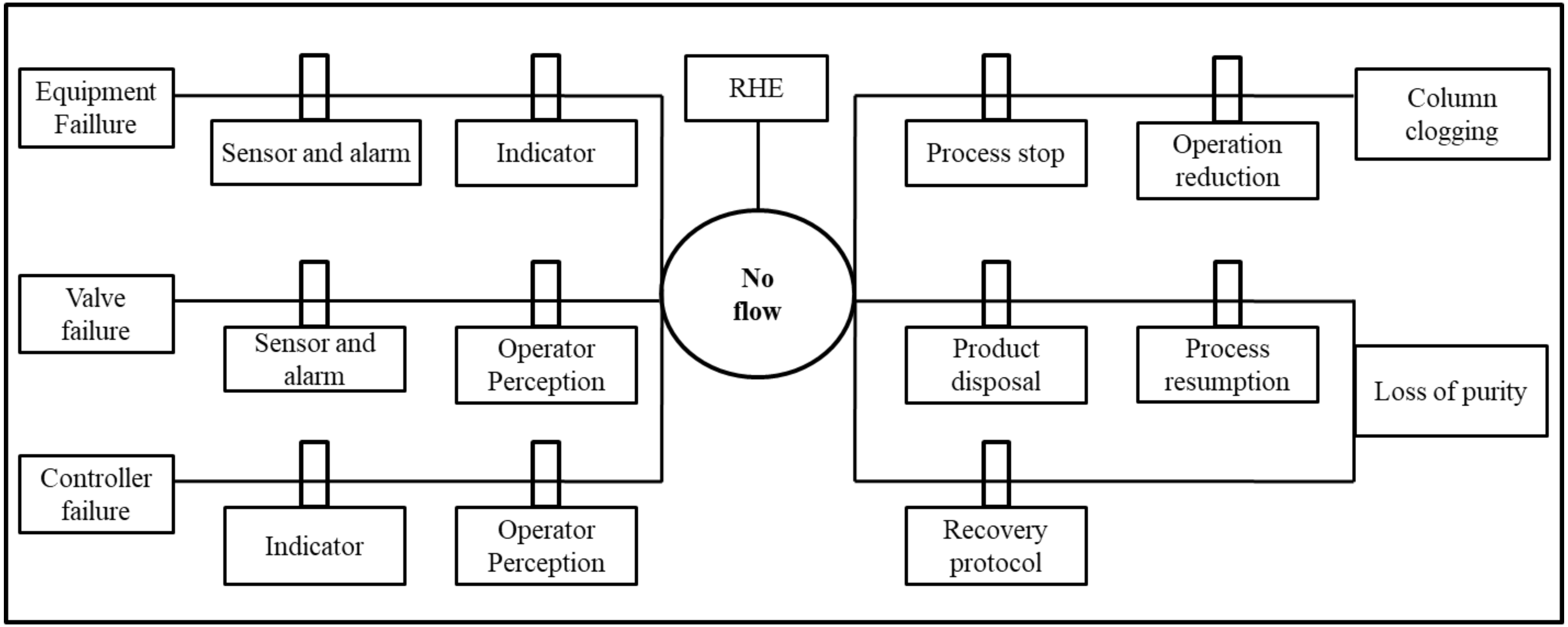


Figure 6 – BOW-TIE applied to "high pressure" risk in the columns

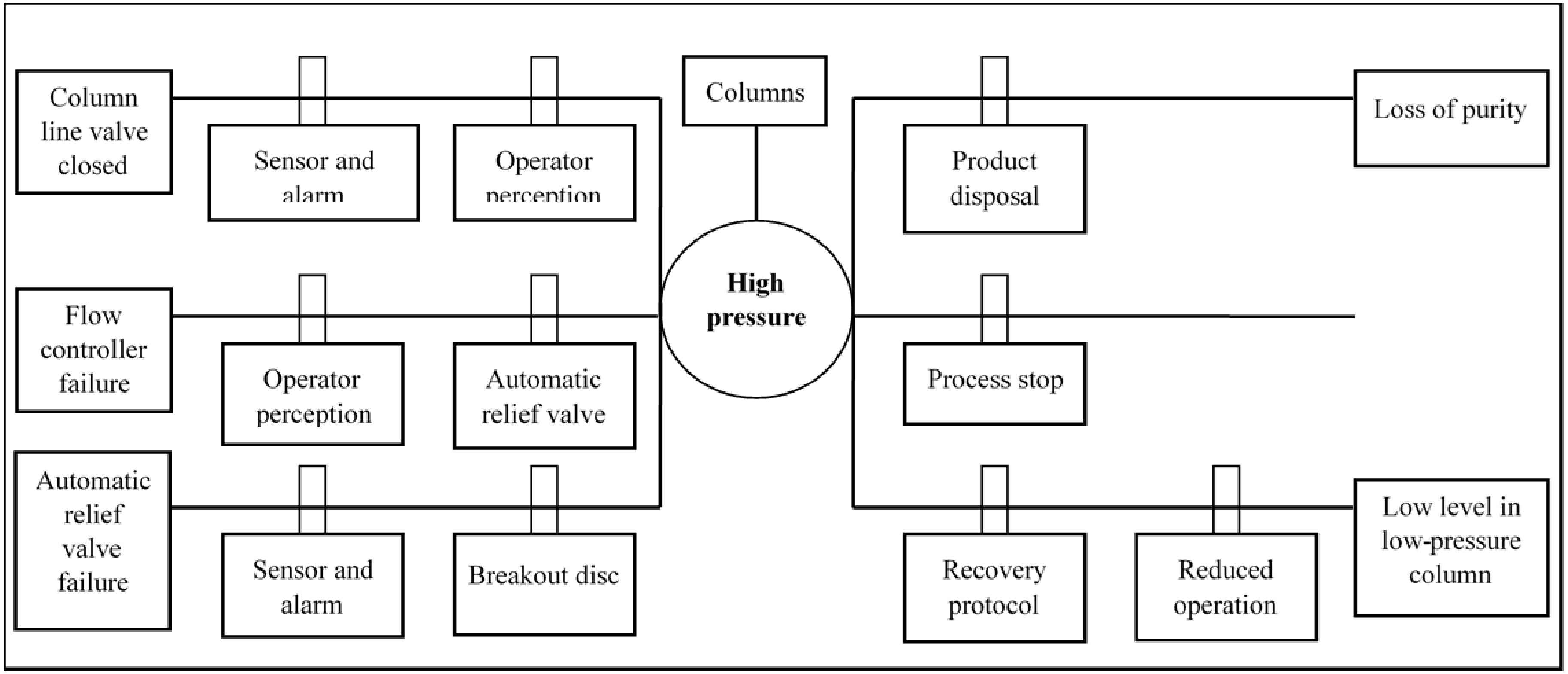
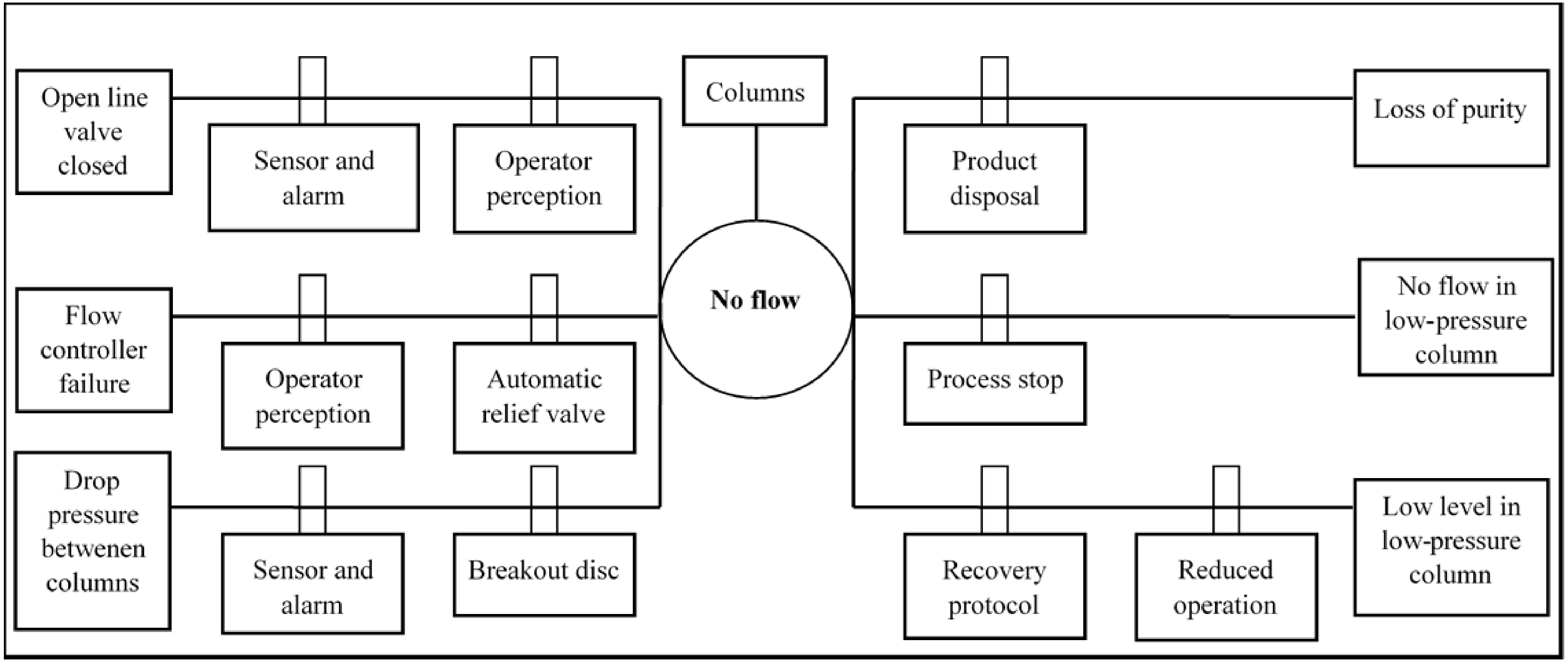


Figure 7 – BOW-TIE applied to "no flow" risk in the columns



The results obtained point to the importance of risk management and the use of tools, in this case HazOp and BOW-TIE that allow defining them. The study makes clear the importance of work of this type for the prevention of losses in processes and lives. Thus, the evaluated data allow the present work to reach the following conclusion.

4 CONCLUSION

In the present work, the risk assessment of a chemical plant that generates gases under cryogenic conditions was proposed. For this, works in the literature related to the theme that could support the research were raised.

With the information collected, it was possible to evaluate the process satisfactorily, even though it was not possible to obtain all the data related to the process, however it was possible to have a global understanding of the process.

The methods used made it possible to assess and identify the risks and classify them, showing that there are high risks in the process that can cause irreparable damage to the process and to people. The results show the importance of risk management in companies and industries and how they enable prevention, thus reducing loss of equipment, money and lives.

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