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MATHEMATICAL MODEL OF RISK MANAGEMENT IN A DEVICE FOR GENERATING ELECTRICITY FROM A SUSTAINABLE HYDROGEN PRODUCTION UNIT

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Abstract. *The aim of the research is to offer an advantageous alternative at zero or negligible level of accident risks, of a solution of autonomy extended to electric vehicles by the installation of an embedded assembly composed of a reactor that produces hydrogen interconnected with a fuel cell. Hydrogen production will be obtained in a reactor by adding aluminum pieces in water catalyzed by sodium hydroxide and the electrical energy to be fed into the vehicle battery will be obtained from this gas when inserted into a Proton-exchange membrane fuel cells (PEMFC). Although, the chemical reaction between aluminum and alkaline solution is strongly exothermic, the gas produced is flammable and permeable in metals, and the chemical agents and residues involved in the process have considerable toxicity. This represents risks to vehicle users, to the environmental conditions where the vehicle will travel and the fire possibility. The extended autonomy proposal to receive approval in the continued manufacturing project of the electrical vehicles, a complementary Risk Management Project (RMP) has become decisive. For this reason, it was found a methodology that has innovative characteristics, such as the conceptualization of what is risk, the technical conducts to the risks identification, those that aim to neutralize or eliminate the identified risks and still, other very interesting that, from the identified risks, it is possible to elaborate a Training Matrix, a PPE Adoption Plan and a Preventive Maintenance Plan. The research will be developed through zero-order mathematical simulations to determine optimal design and operation parameters for the best possible performance with zero risk or at least acceptable level. The study will start from the zero condition of the system, when the yield of electricity production will be evaluated. At same time, considering the risks identified in the operation of the system a Risk Management Project (RMS) will be developed to neutralize or to minimize and to control the risks. Once defined, these actions will be implemented in the system and a new round of tests will be performed and the new results will be compared with the initial condition. Identifying differences, adjustments both in the operating conditions of the system and in the guidelines of the RMP should be made and new and subsequent starts of tests should be performed until the ideal condition of energy production with at least acceptable risk is obtained. In an innovative way, a RMP will be conceived within a technical development project of a device of relevance to the automotive industry, in order to offer acceptable conditions of risks to users, the environment and fire.*

Keywords: Risk Management, Mathematical Model, Hydrogen production

1. INTRODUCTION

The chemical industry plays an important role in national and global economic development, due to its different sectors of activity (industrial chemicals, pharmaceuticals, cosmetics, food, energy, mining, fertilizers, among others). However, chemistry industry has a high risk due to fire, explosion and other accidents, such as the case of Brumadinho and the explosion in the Port of Beirut (Cheng et al., 2021).

Among the sectors of the chemical industry that have been gaining attention worldwide is energy, mainly due to climate problems related to the use of fossil fuels, the replacement of energy sources by environmentally balanced ones is urgent to decarbonize the planet. One of the biggest causes of these climate deviations is carbon dioxide that, among others, has been continuously generated by motor vehicles powered by fossil fuels.

In this context, the 26th United Nations Climate Change Conference (COP26) reaffirmed the Paris Agreement goal of keeping global average temperature below 2 °C, in order to achieve this goal, efforts are being made to reduce carbon dioxide emissions that contribute to reducing air pollution in the electric power sector because greenhouse gas (GHG) emissions and air pollution come from common sources, i.e. fossil fuels (Jiang, 2023).

Thus, the chemical industry plays a key role in the transition to renewable energies, as a promising alternative solution is to replace the energy source of these vehicles is hydrogen, contributing to a sustainable energy future and decarbonizing the planet (Dincer and Aydin, 2023). As hydrogen is a dangerous gas, classified as risk level 2 (ONU 1049) (CETESB, 2023), risk management tools become essential.

Therefore, in order to make successful risk management of chemical industrial accidents, it is necessary to make effective risk analysis and assessment of them even in cases of activities that have risks of low intensity, thus, a well improved and complete Risk Management Project (RMP) it is currently a tool of high importance (De Silva et al., 2022). Previous works have proposed practical methods for risk management and risk analysis of chemical industry, such as hazard and operability (HAZOP), layer of protection analysis (LOPA) and other methods (Nguyen et al., 2022; Yan et al., 2022). In this work, we adopted the development of a zero-order mathematical model for a sustainable hydrogen, electricity and associated risks generation system, integrated with the HAZOP method (Mokhtarname et al., 2021; Minkowycz et al., 2006).

Thus, this project proposes the development of a RMP to be applied in a device that aims to extend the driving range for electric vehicles from the generation of sustainable hydrogen on board and the use of a proton exchange membrane fuel cells (PEMFC) to generate enough electrical energy for the continuous charging of the batteries that power the electric motors of these vehicles.

In addition, when analyzing the technological possibilities for the production of H₂ and that can become part of vehicles with internal combustion engines (H₂ directly replaces the fossil fuel) and even electric ones (H₂ is used to generate electric energy through fuel cells) is the production of sustainable hydrogen embedded in the vehicle itself using reaction of aluminum and water catalyzed by sodium hydroxide, without the need for energy consumption.

Therefore, considering the reaction of aluminum and water, it is noteworthy that currently, aluminum has a very well-established recycling chain, which contributes to the process being sustainable, however, analyzing the reaction, there are several aspects to be evaluated: i) risks of the gas itself, which is very permeable and flammable; ii) the use of sodium hydroxide in the production of H₂ in situ, which has high toxicity, and iii) the reaction is exothermic, bringing risks to users when the need for intervention in the system. Thus, the use of this system must be preceded by a detailed analysis from the point of view of the risks related to vehicular use, in parallel with the development of the whole system.

It should be noted, that a study of the functionality of the set, devoid of a risk management project, hardly achieves approval within a project of continued manufacture of an electric vehicle. A complementary RMP is essential to ensure the safety of vehicle users and the environmental conditions of the surroundings.

In addition, this work contains interesting innovations for the area of risk management system, such as the risk/danger concept, risk identification procedure, risk definition index and extended autonomy for electric vehicles.

In terms of the risk/hazard concept, this paper presents a new technical concept about risk that will be decisive for any risk management project. While for the risk identification procedure, a new technical methodology was developed to effectively identify all related risks. As for the risk definition index, this study is used the better practices on how to qualify the risk indices through new likelihood factors concept. And finally, the extended autonomy for electric vehicles, presents an unprecedented character, with the definition of the ideal operating parameters of a system composed of a hydrogen generator with PEMFC with compatible risk conditions, it is emphasized that with this device, it is possible to increase the autonomy of electric vehicles with the simple use of soda cans.

Therefore, based on the need for a concrete assessment of the risks involved in the development of a new system with the potential to cause bodily injuries, damage to the environment and to the facilities, this work proposed modeling and simulation of sustainable hydrogen generation, electricity and associated risks.

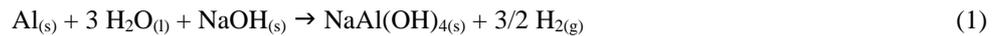
2. METHODOLOGY AND MATERIALS

Initially, it is important to highlight that this study look for the development conditions, operating and risk conditions of a sustainable hydrogen generation unit with fuel cell that may be installed either in an electric vehicle. Thus, in order

to be able to characterize the work and demonstrate the innovation of the study, a bibliographic review is conducted on the topics related to the subject, with the objective of characterizing the state-of-the-art in the theme and identifying the existing gaps for scientific advancement in the area.

2.1 Hydrogen generation reactor

For energy production that can extend the driving capacity of electric vehicles, one of the components of the set to be installed in these vehicles is the reactor that will produce hydrogen. The basic principle of this process consists in the formation of the gas through the reaction of metallic aluminum that can be added to an aqueous solution of NaOH contained inside the reactor, as follows (Soler et al., 2007; Huang et al., 2013; Martinez et al., 2005; Jung et al., 2008).



The general reaction is expressed in Eq. (3). The products are aluminum, sodium hydroxide and hydrogen (Soler et al., 2007; Huang et al., 2013; Martinez et al., 2005; Jung et al., 2008). The aqueous solution of sodium or potassium hydroxide catalyzes the reaction, and they can be recovered. Soler et al., 2007 indicate that in this reaction aluminum can be passivated, and using seawater prepared with NaAlO₂ this effect can be avoided. Therefore, seawater is more efficient than fresh water for the production of H₂.

The proposed system is totally sustainable, since there is no need to contribute energy to its operation. In addition, aluminum and NaOH are used, which are abundant substances in nature and of low cost.

Despite the chemical viability and abundant supply of reagents, aspects of yield, safety and risk need to be addressed in depth to enable the production of H₂ on a large scale, since the reaction shown in Eq. (3) is highly exothermic, which allows the combination of obtaining heat and electricity to seek increase the efficiency of systems (Haller et al, 2021). In addition, reactors producing H₂ from Al must be properly sized to withstand high pressures and temperatures and allow for safe operation (Hurtubise et al., 2018).

Figure 1 demonstrates an example of Hydrogen Reactor:

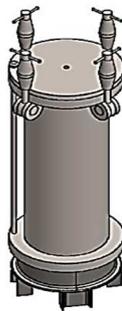


Figure 1. An example of Hydrogen Reactor.

2.2 Proton Exchange Membrane Fuel Cell (PEMFC)

The second equipment under discussion is a fuel cell consisting of a PEMFC. It receives this name, since it contains a polymeric membrane that separates the electrodes and allows the passage of protons, being an electrically insulating material (Raimundo, 2019; Vargas et al., 2010).

Being an electrolytic processing, the objective of this set is to proceed with the transformation of the hydrogen coming from the reactor into electrical energy and that can be supplied continuously to the battery of the vehicle. The H₂ coming from the reactor is injected over the anode of the system that contains an appropriate catalyst, which promotes the oxidation of gas producing electrons (Raimundo, 2019; Vargas et al., 2010).

The polymeric membrane separates the two electrodes, acting as a solid electrolyte. It is permeable to the hydrogen ion (proton), allowing these ions to migrate to the side of the cathode (Raimundo, 2019; Vargas et al., 2010).

At the cathode side, oxygen is reduced by reaction with hydrogen ions coming from the anode, promoting the formation of the water molecule that is normally released into the environment (Raimundo, 2019; Vargas et al., 2010).

The electrons produced in the anode flow down the path of least resistance through an external charge to the cathode, generating the electric current. This electrons in form of electric energy will supply the vehicle's battery (Raimundo,

2019; Vargas et al., 2010). The main components of a PEMFC stack are bipolar plates (BPP), membrane electrode assembly (MEA), and gasket, as presented in Figure 2.

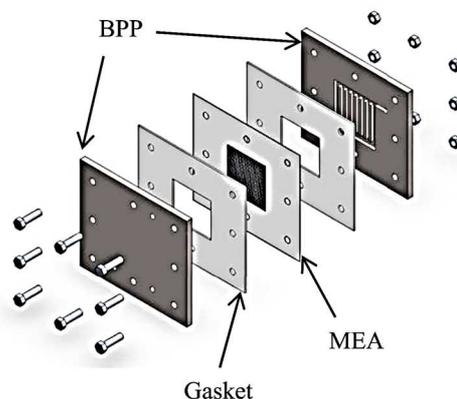


Figure 2. An example of PEMFC (Omrani and Shabani, 2017).

2.3 Mathematical modeling

Major accidents can not only result material losses to the installations and cause irrecoverable damage to the environment, but can also lead to the human life. HAZard and OPERability (HAZOP) method is one of the most widely used and an accept techniques to assess the risks that can result in inconvenient and negative changes and be a tool to identify safeguards to avoid those situations.

However, the method is a subjective qualitative approach to engineering judgment of the HAZOP team. Thus, the integration of mathematical modeling with the HAZOP study, called the HAZOP quantitative dynamic study is necessary for the providing new systems evaluation a quantitative analysis of risks in order to avoid bodily injuries to people and environmental impacts on the environment. Few studies in the technical literature present the role of quantitative dynamic HAZOP and its capabilities (Mokhtarname et al.; 2021). This then identifies the shortcomings of this integration that need to be addressed in order to achieve the full potential of this approach (i.e., especially for complex systems).

The actual study is a combination of mathematical modeling for the identification of the ideal operating conditions of a set of hydrogen production with PEMFC cell followed by the HAZOP evaluation if this condition represents the best alternative for risk management. Initially, the ideal condition of operation of the set is obtained and then the comparison of this condition with the others is carried out to verify which is the one that has the best safety conditions for the facilities, for man and for the environment.

2.4 Risk management

New products often define an industry's competitive advantage and market success. However, only a part of new product development (NPD) initiatives results in success and this therefore represents one of the major causes of wasted investments. In addition, NPD processes have become very complex and risky due to globalization as well as public demands for safe and technologically advanced products (Chauhan et al., 2018).

In this context, it is important to highlight that all decision making is an opportunity to assess the situation of risk-benefit relations and, cause and effect (Chauhan et al., 2018). Therefore, risk assessment, whether carried out or by subjective impulse and even by in-depth and detailed technical analysis of the case, is part of people's daily lives.

The HAZOP methodology is a Process Risk Analysis technique used around the world to study not only the hazards of a system, but also its *operability* problems, exploring the effects of any deviations from design conditions. Dunjo et al. (2010) comprehensively documented HAZOP which covers all aspects of risks addressed in this project, gathering HAZOP-related literature from books, guidelines, standards, scientific journals and conference proceedings, with the aim of classifying the research conducted over the years and defining the state of the art of HAZOP.

In order to substantiate this study, it was necessary to define the technical concept for the term risk. Wagner and Bode (2006) refer that risk, in the context of safety at work and environmental protection techniques, is considered as something that can result in negative consequences. Tohidi, (2010) conceptualizes that risk is a *threat* (*hazard* and *threat*) existing in systems that can result in adverse effects. Several bibliographic sources offer different technical concepts about risk, however, the one that comes closest to characterizing that risk is a source that can result in adverse effects is the one contained in the glossary of the technical standard ISO 45.001, (2018) that conceptualizes "*hazard*" as "*source with a potential to cause injury and ill health*". In the same vein, Mayer et al. (2022) presents as an understanding for the term hazard, the existing condition dependent on the vulnerability of its target object to determine adverse effects of

varying intensity. It further conceptualizes risk as the potential for a given threat to exploit the vulnerability of an asset or group of assets causing harm to the organization (Mayer et al., 2022).

According to the information presented above and developing the practical research, this study defines as risk/hazard the following technical understanding: "*forms of energy that when reach man, environmental conditions or some installation result in adverse effects*". To consolidate this concept, it can point out when more intense is the form of energy, more severe the related effects will be. Hence, hazardous energy can be understood as: "*A condition inherent in a form of energy (chemical, mechanical, electrical, potential, light energy, radioactive or another) which, when out of control, hits the worker's body will causes bodily injuries or reaches the environmental condition will results adverse impact of various levels of severity*".

Considering that risks are forms of energy and because they are transient, it can be understood that they can be found in the systems inputs and outputs. In this understanding, the safe and effective conduct to proceed to the identification of risks of an activity is through the methodology that is called "*Inputs and outputs*". That is other good innovation of this research.

Risk assessment (RA) and life cycle assessment (LCA), which use input-output theory, are two analytical tools used to support decision-making in environmental management (Harder et al, 2015).

In the sequence of the study, the next step is to define the risk index of each identified risk. This task consists of combining the factor of severity with the factor of probability of realizing a risk-related effect. For that, there is a need to identify the effects associated with the risks and the causes related to these effects. To identify the effects, it is necessary to have experience in the object of the study and to be able to identify the causes of the effects, the teachings of Ishikawa recommend that the technique called "*Fishbone*" must be employed (Assumpção, 2022; Harder, 2015). This methodology indicates that, conceptually, the causes of effects are those related to six factors: i) labor (malpractice, recklessness and negligence), ii) the method used to perform the task, iii) the conditions of the machine or installations, iv) the environmental conditions, v) the materials involved and vi) interference from other aspects (Assumpção, 2022; Harder, 2015).

To define the severity and likelihood factors, the scales were adopted shown in Table 1 and 2.

Table 1. Scale for severity of effects (Assumpção; 2018).

SEVERITY		
FACTOR	EFFECT	CRITERION
1	MILD	Accidents that do not cause bodily injury (e.g., light scratches, etc.);
2	MODERATE	Accidents that cause non-disabling injuries (e.g., burns with redness on the skin, etc.);
3	MAJOR	Accidents that cause disabling injuries without loss of substance (e.g., deep and serious burns, etc.);
4	SEVERE	Accidents that cause disabling injuries with loss of substance (e.g., loss of part of fingers, etc.);
5	CATASTRÓPHIC	Death

Table 2. Scale for likelihood (Assumpção, 2018).

LIKELIHOOD		
FACTOR	OCCURRENCE	CRITERION
1	UNLIKELY	Very low probability of damage occurring. (One occurrence over a large period of time, one every ten years or so)
2	POSSIBLE	Low probability of damage occurring. (One occurrence in the last five years)
3	OCCASIONAL	Moderate probability of damage occurring. (More than one occurrence in the last three years)
4	REGULAR	High probability of damage occurring. (More than two occurrences in the last two years)
5	CERTAIN	Very high probability of damage occurring. (at least one occurrence is expected in the next twelve months)

According to the results obtained with the severity with the likelihood, it is possible to define the risk index and the corresponding actions according to the information contained in the Table 3:

Table 3. Actions management (Adapted from Assumpção, 2018).

ACTIONS MANAGEMENT		
RESULT S x L	RISK INDEX	ACTIONS
<i>Up to 3</i> (severity < 3)	TRIVIAL RISKS	They do not require special actions, neither preventive nor detection.
<i>From 4 to 6</i> (severity = 3)	TOLERABLE RISKS	Do not require immediate action. They may be improved at an appropriate time depending on the availability of manpower and financial resources
<i>From 8 to 10</i> (severity = 4)	MODERATE RISKS	Requires prediction, definition (short term) and responsibility for the implementation of actions;
<i>From 12 to 16</i> (severity = 5)	RELEVANT RISKS	Requires the immediate implementation of actions (preventive and detection) and definition of responsibilities. The work can be released for its execution only with continuous supervision and monitoring. The interruption of work can happen when the conditions present some lack of control;
<i>> 16</i>	INTOLERABLE RISKS	The work cannot be started and, if it is ongoing, it must be stopped immediately and can only be restarted after implementation of containment actions.

With the information regarding the effects and causes of the accidents, due to the proposed methodology having safe guidelines, a consistent Preventive Action Plan can be developed. It is also important to note that, to avoid adverse effects, hazardous energy can be neutralized or controlled through preventive measures. Preventive actions can neutralize or eliminate the hazardous energy.

Once the effects and causes related to the risks are identified, it is possible to establish the risk indices of each related cause. Subsequently, the Preventive Action Plan must be defined and implemented (Assumpção, 2018; Dunjo et al, 2010; Harder et al. 2015).

Once preventive actions are implemented, it is expected that the likelihood outcomes are likely eliminated or at least minimized. In most technical aspects, such as the installation of energy control devices, the adoption of physical protections (limits, barriers, defenses), the establishment of preventive actions is effective. Above all, according to Assumpção (2022), it should be noted that human behavior is diverse, technical preventive actions do not always effectively interfere in aspects related to negligence and recklessness. It states that, even with well-established and properly implemented preventive actions, negligent and reckless behaviors are still identified. It states that negligent behavior is more susceptible than reckless behavior. Cases of negligence are more predictable than reckless ones (Assumpção, 2022).

To define the severity factor, regarding the effects that accidents with sodium hydroxide can cause, Schwartsman (1991) states that dermal contact results in severe extremely painful burns. There is an initial edema with formation of vesicles and then occurs necrosis of liquefaction that progressively deepens. In the eyes, rapid and little intense exposure produces conjunctivitis, lacrimation and photophobia. In the most severe cases there are severe pain, edema of the conjunctiva and eyelids and corneal ulceration. It has a lethal dose of 5.0 g.

2.5 Practical development

This research project aims to make complete risk management study to identify the condition of greater amount of hydrogen produced under condition of lower risk of accidents for the users of the vehicle when they have to operate the system involving a hydrogen generator set and fuel cell, focusing on the following aspects:

- Chemicals and energies: alkaline solution, aluminum, hydrogen, sodium aluminate and electrical energy;
- Equipment and accessories: reactor, pipes and fuel cell;
- Activities: preparation of the alkaline solution, removal of waste generated in the reactor, operating conditions of the set.

For this work, only the preliminary part of the research related to the RMO of the conditions of preparation of the alkaline solution of the hydrogen reactor will be demonstrated.

The study of the following variables will be reported: type of caustic soda to be used (pellet or liquid, concentration 50%) and the concentration of the solution to be defined (1.0; 3.0; 7.0 or 12.5 M). This research will have as final objective to obtain the conditions of lower risk to the user, the environment and fire occurrences, associated with the conditions of obtaining the highest yield of hydrogen production.

The search sequence must be followed as shown in Figure 3.

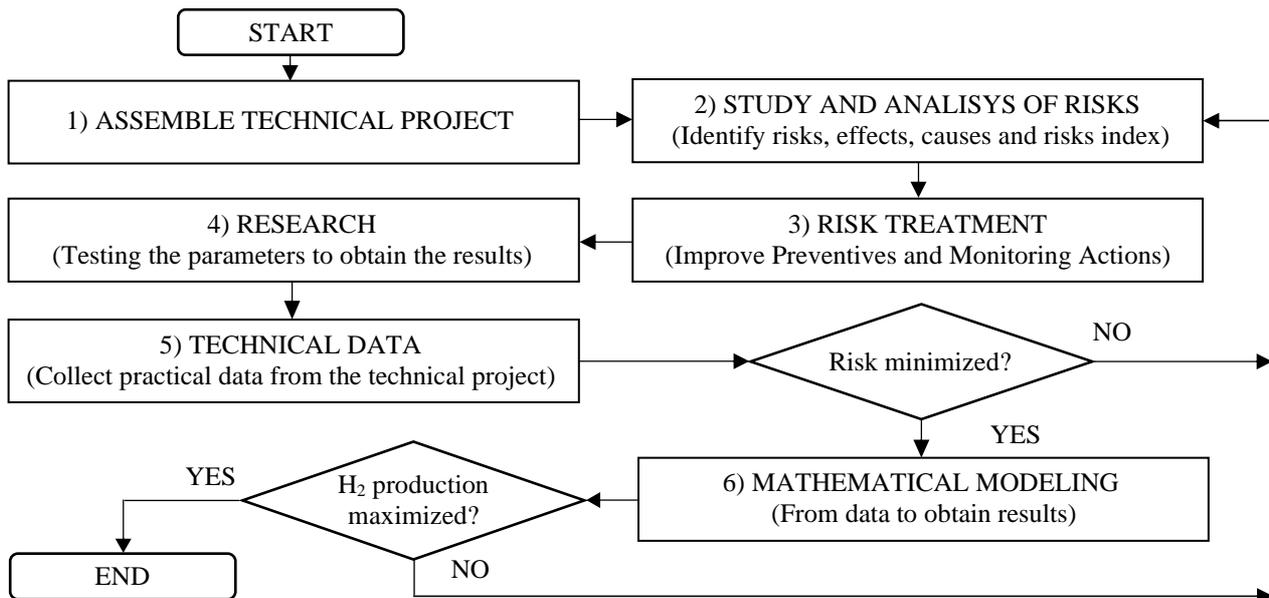


Figure 3. Flowchart adopted for work.

As a reference for the development of this case study, it will be evaluated the risk conditions that a family of a couple plus two children undergo when they make a long-distance trip with an electric vehicle that has the presented device. All have basic knowledge of the operability and risks existing in the system. At the beginning of the trip, they make all the preparations of the system by adding the caustic soda lye solution to the reactor. Every 200 km (2,5 hours), they take a break for a snack and each one takes a can of soda. Before resuming the trip, the driver adds these four cans of soda to the reactor to produces hydrogen and electrical energy.

The objective of the study is to identify which is the condition of lowest risk for vehicle users, when varying concentrations of alkaline solution are used (caustic soda (1.0 molar, 3.0 molar, 7.0 molar or 50% soda (12.5 molar)) and when solid caustic soda (pellets) or liquid caustic soda (50% by weight), the commercial one, is used. Consider that, through market research, it was identified that liquid caustic soda has a price by weight 30% higher than solid soda.

For the purpose of the research, it was considered that the higher the concentration of the alkaline solution, because it contains a greater amount of energy, the more intense the risks will be, however, the greater the use of the solution and the lower the exposure of users to the risk, which results in a lower probability of accidents.

It should be considered that a can of soda has a weight of 15 grams. The volume of the hydrogen reactor has a capacity of 18 liters and that the alkaline solution will occupy 50% of this volume (9 liters). Assuming reaction (3) above, without considering the reaction kinetics and aluminum alloy composition of soda cans, it is understood that 40 grams of caustic soda will be required to consume 27 grams of aluminum from soda cans.

The practical experiment was conducted as follows:

The research was developed only in the study of existing risks in the hydrogen production reactor. For this purpose, the methodology of inputs and outputs was used, encompassing the following steps:

1st Step – Identification of risks: for this purpose, the methodology of “*Inputs and outputs*” was adopted and among the results are sodium hydroxide and perform tasks of feeding reactor with sodium hydroxide.

2nd Step – Characterization of risks: In order to establish the risk indices of each risk, the related effects and the corresponding causes must be defined. After that, the factors related to the effects and causes should be defined. The predictable effects on vehicle users in relation to a sodium hydroxide accident is the burning of the skin or eyes. The corresponding severity of this effect will be a function of the concentration adopted for the alkaline solution.

In order to define the likelihood of accidents with sodium hydroxide, Table 4 was established:

The information shown in the columns in this table is as follows:

- Concentration: of the alkaline solution referring to 1.0 M; 3.0 M; 7.0 M (caustic soda in pellet) and 12.5 M (50% liquid caustic soda);
- NaOH pellet: amount of NaOH pellets required to form the alkaline aqueous solution with water;
- NaOH liquid: amount of 50% liquid NaOH to be added and amount of water to assemble the solution;
- Can: number of cans to saturate the solution; obtained from the reaction (3)
- Time to replacement: time of use of the alkaline solution, when one has to replace the solution;
- Intervention factor: Number of times one has to intervene to prepare new solutions. It is taken as a basis (factor equal to 1,0) for the case in which the alkaline solution is used for a longer time (12.5 M alkaline solution).

Table 4. Likelihood of accidents with sodium hydroxide.

ITEM	CONCENTRATION	PELLET	LIQUID	CAN	TIME TO REPOSITION	INTERVENTION FACTOR
1	1.0 M (40g/l)	360 g	720 ml + 8,280 ml H ₂ O	17	10h	12.5
2	3.0 M (120 g/l)	1.080 g	2,160 ml + 6,840 ml H ₂ O	49	30h	4.2
3	7.0 M (280 g/l)	2.520 g	5,040 ml + 3,960 ml H ₂ O	114	71h	1.8
4	12.5 M (500 g/l)	4.500 g	9,000 ml + 0 ml H ₂ O	203	126h	1.0

Through what is shown in the right column of the table above, it is identified that for each time when need to replace the alkaline solution using the 50% liquid caustic soda one has to proceed 12.5 times to obtain the 1.0 M solution of the pellet soda.

Usually, to obtain the risk index, the result of multiplying the factors of severity of the effect with the likelihood of effectiveness of this effect is used. One of the innovations of this project is that to obtain the risk index for the factor likelihood is used the factor of the probability of the effect combined with the factor of the probability of the causes. It was observed that when only the probability of effecting the effects is used the interferences of the causes are not considered. Doing as it is being proposed, it is observed that the results obtained are more realistic.

Considering that when using pellet soda at the concentration of 1.0 molar it is necessary to prepare this solution 12.5 times than when using liquid soda. It is admitted that the probability of accidents (effects) for the use of the solution prepared with pellet soda receives the likelihood factor 2 and for the liquid soda factor 1. Then, upon this consideration and combining the likelihood factors of the effects and the causes, the results are as shown in the Table 5:

Table 5. Combining the likelihood factors of the effects and the causes.

KIND OF SOLUTION	LIKELIHOOD OF CAUSES	LIKELIHOOD OF EFFECTS (POSSIBLE (2))
LIKELIHOOD OF CAUSES (NaOH in pellet; 1.0 M solution)	Others factors: NaOH contaminated (1)	UNLIKELY (1)
	Environment: noise, rain, and others (2)	POSSIBLE (2)
	Workforce: inexperience. (2)	OCCASIONAL (3)
	Workforce: reckless, negligence (3)	
	Method: unappropriated utensils (2)	POSSIBLE (2)
	Materials: unappropriated PPE, equipment and utensils (2)	OCCASIONAL (3)
	Machine: feed point is too small (3)	
KIND OF SOLUTION	LIKELIHOOD OF CAUSES	LIKELIHOOD OF EFFECTS (UNLIKELY (1))
LIKELIHOOD OF CAUSES (NaOH liquid 50%)	Others factors: NaOH contaminated (1)	UNLIKELY (1)
	Environment: noise, rain and others (2)	POSSIBLE (2)
	Workforce: inexperience. (3)	
	Workforce: reckless, negligence (3)	UNLIKELY (1)
	Method: unappropriated utensils (2)	
	Materials: unappropriated PPE, equipment and utensils (2)	
	Machine: feed point is too small (2)	

According to the information shown above, the Risk Matrix for the preparation of the alkaline solution with caustic soda in pellets at a concentration of 1.0 molar and with liquid caustic soda 50% is shown on Table 6.

Table 6. Risk Matrix.

ITEM	RISK	EFFECT	CAUSE	RISK INDICE			
				S	L	S x L	RISK INDICE
1	Sodium hydroxide (pellet); Perform tasks of feeding reactor with sodium hydroxide	Burns in the Skin and eyes	Others factors: NaOH contaminated	3	1	3	Tolerable risk
2			Environment: noise, rain...		2	6	
3			Workforce: inexperience.		2	6	
4			Workforce: reckless, negligence		3	9	Moderate risk
5			Method: unappropriated utensils		2	6	Tolerable risk
6			Materials: unappropriated PPE, equipment and utensils		2	6	
7			Machine: feed point is too small		1	3	
8	Others factors: NaOH contaminated	1	3				
9	Sodium hydroxide (liquid 50%); Perform tasks of feeding reactor with sodium hydroxide	Burns in the Skin and eyes	Environment: noise, rain.	3	1	3	Tolerable risk
10			Workforce: inexperience.		2	6	
11			Workforce: reckless, negligence		2	6	
12			Method: unappropriated utensils		1	3	
13			Materials: unappropriated PPE, equipment and utensils		1	3	
14			Machine: feed point is too small		1	3	

This same table was prepared to be able to compare the risk indices for solutions of the same concentration (12.5 M), however, one prepared with solid soda and the other with 50% liquid soda.

For this study, worksheets were prepared containing preventive actions for the causes and for the effects for all the proposed situations and the summary was as follows: automate the equipment that proceeds to the supply, both for solid soda and for liquid soda; provide PPE and apply training to users.

Subsequently, the studies are directed to the process of identifying the alternative to obtain the maximum production of hydrogen. Identifying this condition, if it is obtained with a concentration different from that established in this study, a new round of risk assessment should be carried out and followed by a study of the maximum point of hydrogen generation, until the maximum condition of production of this gas with minimum risk is obtained.

3. RESULTS AND DISCUSSION

Noteworthy that more concentrated solutions require fewer interventions of users in the preparation of new solutions, which denotes a lower probability of accidents occurring. For this reason, more concentrated solutions are preferred.

Through the observations obtained in the tables presented, even having a higher cost, it was identified that the use of 50% liquid caustic soda has significant advantages, since it does not require dilution with water, the solution is already ready for use (one less risk, splashes); does not cause heating of the solution when dissolving with water, which the dilution of solid soda causes (avoids risk of burns in users) and does not cause the formation of strongly alkaline vapors that are generated in the reaction of solid soda with water (one less risk, burns of the user's respiratory system).

4. CONCLUSION

It is concluded that, through risk management analysis, the use of liquid caustic soda is in commercial terms a more practical option and presents a lower probability of accidents, making it the best alternative. It should be noted that the proposed methodology for risk identification presented a more complete, consistent and devoid of weaknesses RMP, addressing the HAZOP method, and combined with the production of sustainable hydrogen for clean energy generation is an unprecedented study and not addressed so far in the literature, demonstrating its innovative and essential character in terms of safety with practical applications in the field of renewable energies that are so necessary today.

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