Analysis of Active Failures and Latent Conditions on Biodiesel Production Facilities

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Abstract—During the last decade biodiesel production facilities have had a fast growth all over the world. Production levels and installed capacity have increased continuously to respond the demands of renewable oils. This growth has been accompanied by increasing accident rates. This fact raises the necessity of understand accidental causes in order to eliminate or diminish them. The present paper applies the Reason' Swiss Cheese model of Human Error to a series of accidents that have taken place at biodiesel facilities in the period 2003 to January 2014. It allows identifying the unsafe acts and latent conditions that have conducted to accidents, and implementing tools to manage them.

***Index Terms*— accidents, active and latent failures, biodiesel, human error.**

I. Introduction

THE first time someone use vegetable oil as fuel could be traced back to August, 1893 when Rudolf Diesel used peanut oil to fuel his prime engine model.

The use of vegetable- based diesel lasted until the twenty's decade and was replaced by fossil-based diesel due to its cheaper price, higher availability and government subsidies [1].

Almost 100 years later, the exhaustion of petroleum reserves and the environmental problems raised the need to find alternative energy sources for its replacement.

Biodiesel is one of the possible alternatives between the renewable energy sources that allows to replace fossil fuels with little or no adequacy of engines, and to reduce toxic emissions. Due to these facts, biodiesel production has increased considerably in the last decade.

Figure 1, obtained using data from the U.S. Energy Information Administration [2], shows the quickly growth on biodiesel production during the last 10 years in main biodiesel producer countries and regions of the world.

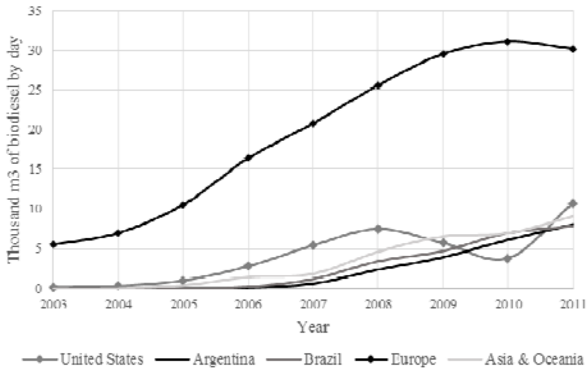

Fig. 1. Biodiesel Production by main producers regions and countries, thousand m3 of biodiesel by day versus year of production.

Increasing of production implies a major installed capacity. According to a report of CADER [3] countries like Argentina, increased production capacity from about 568 thousand m^3 of biodiesel in 2007 to more than 3,41 million m^3 in 2012. The same report stated that in the year 2010 there were 245 plants in European Union, 151 in United States, 63 facilities in Brazil, 53 in Spain and 23 in Argentina.

The production growth has been accompanied by an increase of accident rates. According to Rivera and Mc Leod [4], [5] incidents have occurred due to the lack of expert operators and safe technologies. The same authors also stated that many plants had been installed since 2010 although there were not a complete knowledge about the biodiesel cycle [4].

More relevant accidents have been presented and some of them analyzed in detail by several authors [4], [6], [7], [8], [9]. However, a framework or a model that allows to understand accident causation on biodiesel plants has not been founded yet.

When studying accident reports it can be expected that the number of accidents diminishes through time as a result of a better understanding of the process and human-machine interfaces. On the contrary, data reveals that the same accident has taken place in different years and industries, and the same consequences (e.g. the total loss of the plant), have been faced by several facilities during the last ten years. In countries like Argentina, at many biodiesel production facilities safety is treated like a secondary cost that should be limited to the minimum when it cannot be eliminated. This occurs due to the belief that the process is simple and do not imply risks [4], [10]. Companies' managers should be conscious that they are obtaining fuels and, although biodiesel is less dangerous than diesel, the

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production process requires reliable storing, transport and control mechanisms and a safe infrastructure.

Transesterification of vegetable oils or animal fats is the most used technique to produce biodiesel. It consists in the reaction of oil with an alcohol such as methanol, in presence of a catalyst, generally a strong base, such as sodium or potassium hydroxide [11]. The storing and handling of these raw materials involves risks for the industrial installations such as fires, explosions and spills. Chemical reactions can also be a hazard if they are not carried out in a correct and safe way.

According to the information founded, excluding those accidents under investigation or with no information about the causes, the 20% of the cases was due to human error. Then, the interest and challenge is to identify and mitigate the causal sequence of events.

Many models and techniques have been developed for the assessment of human error, especially in Nuclear and Aviation areas. However, specific methods to analyze and classify errors in biodiesel plants have not been founded yet, although the increasing rate of accidents raises the need of doing it.

The objective of the present work is to apply the model known as "Swiss Cheese" proposed by James Reason [12], [13] to a record of 86 accidents that have occurred at Biodiesel plants since the year 2003 till January 2014. This will allow to develop a framework to understand the causes in a better way. Data were obtained through the analysis and collection of information from different documental sources such as newspapers, magazines, technical reports and bibliography.

II. The 'Swiss cheese' model of human error

In the year 1990, James Reason [14] did an important contribution developing a "model" of how accidents could be seen not simply as a consequence of human error, but as the result of the relationship between "unsafe acts" (active failures) by operators and latent conditions of the system. The model, known later as the "Swiss Cheese model", resulted very pedagogical and many accident analysts started to apply it in different industrial domains such as nuclear, aeronautic and health care [15]. It was evolving through the years, from the first one that consisted in five "planes" with benign and pathological aspects (top level decision makers, line management, preconditions, productive activities and defenses) to the last one in which there were three elements: hazards, defenses and losses, and the "planes" were replaced by Swiss cheese slices that represent all the many barriers, defenses, safeguards and controls that a system should have (Fig.2).

According to the resulting model [12], [13] accident causes are due to the successive penetration of the defenses by either active failures or latent conditions. Active failures are defined as *unsafe acts* made by operators and they involve errors and violations. Latent conditions, the "pathogen agents" include contributory factors that may dormant in the system until they contribute to an accident (e.g. organizational culture, management decisions, procedure design, or deficient training).

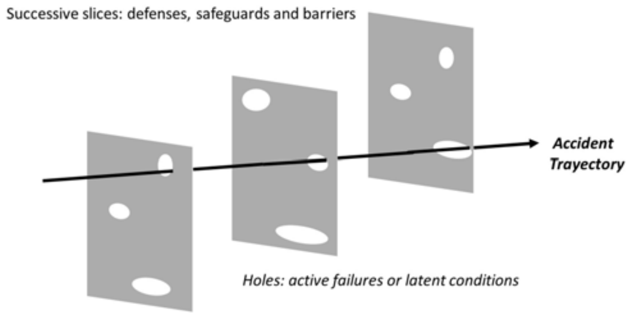

Fig. 2. Reason Swiss cheese Model, 2000.

According to Shappell and Wiegmann [16] although this model revolutionized common views of accident causation, it is a theory in which the "holes in the cheese" are not defined clearly. For an accident investigator it is crucial to know what these system failures or "holes" are, in order to be detected and eliminated to avoid accident occurrence. In previous work [10] several latent failures on biodiesel small- scale production plants were identified and the associated problems or consequences for the system. It is the objective of the present work to describe, in a similar way that was done for aviation, what the holes in the slices are (active and latent failures) according to a register of 86 accidents occurred at biodiesel plants between 2003 and January 2014.

III. Modeling errors on biodiesel plants

1. Unsafe Acts

According to [14] *unsafe acts* can be divided in errors and violations. Error is defined as an action not perform as intended and it can be reduced by improving the quality and availability of information processed by human. Violations are deviations from normal operating procedures, rules and regulations, and require motivational and organizational changes to be reduced.

Reason states that these human actions are then classified as:

- Skill-based: actions routinely practiced and highly automatic.
- Rule-based: actions are the result of conscious and unconscious processes to respond to a situation met before, either through experience or training.
- Knowledge-based: actions that require slow, demanding, and highly-error prone conscious thought to respond when other methods resulted unsuccessful.

Human errors founded in the 86 collected accidents were mode using Reason's classification previously explained. Accidents or incidents involving knowledge-based mistakes and violations were not founded. Next, results are presented.

1.1. Skill-based errors

The study of information collected about accidents on biodiesel plants allows finding the following skill-based errors:

- *Attentional slips*: occur when the operator fail to monitor the progress of routine actions at some critical point [17]. An example for this type of error was the accident that occurred when a transfer of a processing- chemical

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mixture was left unattended, causing a small tank overflowed. The mixture ran across a driveway into a small inlet along a local river [18].

- *Memory lapses*: took place when the person forgets what earlier intended to do or when steps from a plan or action or procedure are omitted [17]. Examples for this type of error involves storage tanks and silos that were left opened, closing valves which were also left opened or process equipment that was left on.

1.2. Rule-based mistakes

An example for this type of error is the improper application of procedures. This occurred in two opportunities, when operators were mixing sulfuric acid with glycerin, during the neutralization step. They introduced 21 times more acid into the vessel than the process was designed for. It created an exothermic reaction that caused an explosion, followed by an spill in one of the cases and by a fire in the other [19], [20].

Other example is the improper disposal of oily rags that have created fires in presence of ignition sources. The plant usually disposed rags (used to clean biodiesel) and filters in a water tank, but that day operators put the rags in a drum not properly contained, they caught fire and damaged a filter press [21].

Table I summarizes the unsafe acts founded on biodiesel plants.

TABLE I
EXAMPLES OF UNSAFE ACTS

Skill-based errors
Inattention during chemical transfer process.
Process equipment left on.
Closing valve of storage silo left opened.
Silo containing flammable material left open to the air.
Glycerin tank left opened.
Rule-based mistakes
Failure to apply chemical mixture procedure.
Failure to dispose oily rags according to procedure.
Failure to apply procedures for welding tasks on tanks and pipes.

2. Latent Conditions

It refers to the conditions that are present in the organization long before a specific incident occurs. Most of them are due to the organization itself, as a result of its design or of managerial decisions. The presence of latent conditions is universal in all organizations nevertheless of their incident and accident record [15].

Next, latent conditions found on biodiesel plants are presented according to the following classification: unsafe supervision, organizational influences and process design.

2.1. Unsafe Supervision

Information analyzed can be *classified in two categories:*

2.1.1. Inadequate supervision

The role of any supervisor is not only to check the others work, but also to provide a guide, training opportunities and to motivate operators to do their work in an efficient and safe way. However, this is not always the case.

Several accidents occurring at biodiesel plants were the result of a poor or inexistent supervision. As previously was mentioned, in two cases [19], [20] operators mixed, during neutralization phase, sulfuric acid with glycerin in an improper ratio. This caused the explosion of the mix vessel as a result of overpressure. If a supervisor had been checking the operation or he had provided the correct training, the accident could have been avoided.

Another situation that repeats are the tasks of welding on tanks that contain or have contained flammable substances, and on pipe parts that in general, are connected to equipment that contain a dangerous substance. In most analyzed cases, this kind of work was made by contractors during the scheduled maintenance of the biodiesel plant. Contractors are usually not employees of the dangerous establishment so the installations and their associated risks are not familiar to them [22]. Supervisor’s function is to communicate working conditions, work environment hazards and to ensure that the contract worker is well trained and know procedures. Unfortunately, this not always occurs and at seven cases [23], [24], [25], [26], [27], [28], [29] contract operators began their welding tasks causing explosions and fires, with fatal consequences. The welding work generates sparks or an increment of temperature that are elemental keys to ignite flammable environments.

2.1.2. Supervisory violations

This category refers to those instances when existing normative and regulations are wilfully omitted by supervisors. There have been cases in which supervisors have not taking in care basic safety measures such as adequate ventilation, or have failing to follow local legislation (e.g. OSHA Acts, Georgia Environmental Acts, etc.).

Table II summarizes the *inadequate supervision* and *supervisory violations*.

TABLE II
EXAMPLES OF UNSAFE SUPERVISION

Inadequate supervision
Failed to provide adequate training.
Failed to check adequate qualification.
Failed to instruct about facility’s hazards.
Failed to provide hot work permissions.
Failed to provide minimal work conditions.
Supervisory violations
Failed to enforce and/or fulfill normative and regulations.

2.2. Organizational Influences

Supervisory and operators practices are affected directly by decisions of upper-level management. Usually, if an investigator do not have a framework to consider and investigate organizational errors, they go unobserved [16]. However, they are an important part of the “pathogens” that contributes to an accident.

According to the accidents collected occurring on biodiesel plants, organizational influences are divided in two groups:

2.2.1. Resource management

This point refers to how resources such as personnel, machinery, tools and equipment, and money are managed in order to achieve the company’s goal of cost-effective operations and safety of the process. However, in times of financial resources austerity, one of the first costs to be cut is safety. For example, until the year 2009 many biodiesel plants in the United States were based on tax credit,

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however it expired causing many plants to reduce installed capacity or shut down operations [30]. Cost-cutting may lead to the purchase of equipment (e.g. storing vessels) that is not optimal and adequate for the operation and the risks involved. Other practices include reducing of maintenance tasks not only for equipment but also for workplaces. The 30% of the studied accidents have been originated by equipment mechanical failures such as motor overheating, thermostat and safety valve failures, between others. These failures that finished in some cases with important consequences like the destruction of a building or equipment, could have being avoided with adequate maintenance.

2.2.2. Organizational process

This category refers to the decisions and rules that conduct tasks on the organization. It includes the use of operating procedures. It has been founded that the use of procedures is not common on biodiesel industry. This originated accidents, as was mentioned previously, due to the lack of knowledge about the proper steps to follow in a chemical reaction (e.g. mixture of sulfuric acid and glycerin).

It is important to point out that when facilities apply not only working procedures but also safety plans and procedures, response of operators in case of accidents is faster. And if the program includes to communicate to local authorities (e.g. fire or police stations) about the facility hazards and substances stored, mitigation procedures are quicker and the magnitude of consequences diminishes.

Table III summarizes *organizational influences.*

TABLE III
EXAMPLES OF ORGANIZATIONAL INFLUENCES

Resource Management
Personnel
Selection process
Training
Financial resources
Cost cutting
Organizational Process
Procedures
Instructions
Documentation
Safety Programs
Process Design
Machinery and Equipment
Use of inadequate engine for pumping methanol
Use of storing tanks of inadequate material
Lack of control about ignition sources in explosive environments
Lack of grounding of the tanks to avoid static loads
Use of metallic tanks with unsafe locked
Building features
Lack of firefighting equipment
Lack of fireproof materials

2.3. Process Design

According to available technical reports of performed inspections at some biodiesel plants [31] organizations fail to have adequate information about the process technologies (e.g. safe upper and lower limits for temperature, pressures, flows and compositions), to perform periodic inspections on process equipment and machinery, and to correct deficiencies noted during equipment inspections.

Other common failure on process design is the lack of correct electrical classification, including proper grounding of storing tanks and equipment.

In other cases, choosing of inadequate material for biodiesel and raw material (e.g. sulfuric acid) storage vessels originated fires and spills of important magnitude [32], [33].

It has also been found the use of improper equipment such as for example, wrong electrical equipment in the control room [31], or the engine of a methanol pump that produced sparks, caused an injured person and the destruction of the plant [34].

Finally, fast spread of fire on most of the accidents shows the lack of fireproof materials, fire detection equipment (e.g. air handlers or smoke detectors) and suppressant systems (e.g. sprinklers).

Figure 3 summarizes the previous analysis. It is an adaptation of the Swiss cheese model to show accident causes on biodiesel plants.

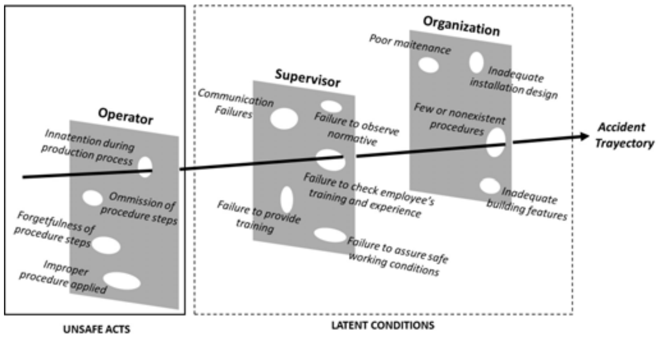

Fig. 3. Adaptation of Swiss cheese model to analyze accident causation on biodiesel facilities.

IV. DISCUSSION

Analysing the exposed results, accidents on biodiesel plants have been the result of a combination of diverse factors among which the human error can be founded.

So far, knowledge about accident causes as a result of human error is limited due to the lack of complete information. This fact restricts the understanding of accidents since do not allow identifying other possible active and latent conditions existing in these complex systems. Data about accidental sequence, mitigation measures and causes is not available for the total of collected accidents. It has been founded that there is not information for the 36% of the accidents and for the 17%, causes are 'under investigation'.

That means loss of information about causes in more than half of the accidents.

This work is an attempt to contribute to general knowledge of accident and incident causation in biofuel industry. However, it is a limited study because of the scarcity of data.

A great effort is necessary to begin reporting and recording useful and complete information about adverse events such as event sequence, mitigation measures, causes and consequences (number of injured people, dead and material damage).

It is responsibility of organization's upper-level to provide the necessary tools and methods to do it. These data

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will help accident researchers to identify more possible unsafe acts and latent conditions that have originated accidents, and that can be also the origin of a different accident or even causing the recurrence of one or more accidental events. As a result, a depth understanding of the causes will be possible.

V. Conclusions

This is a first approach to model human error on biodiesel plants. The error models and taxonomies provide a useful framework to obtain information about the causes of an accident and understand its underlying error mechanisms. Once a type of error has been identified and associated to specific conditions or scenarios, it can be replicated through simulation. This makes possible to investigators obtaining a better knowledge about it and proposing the mechanisms to eliminate it.

According to analyzed data it is crucial to train personnel, providing safer working procedures, both for normal and for abnormal operating situations, and to ensure a good level of supervision on biodiesel plants.

When working with contractors, it is recommended that facilities implement the use of hot working permissions and previously to do the maintenance tasks, contractors should be communicated about the installation hazards. It is also a safety practice that supervisors be sure about the experience and training of the contractor.

It is also important to assure through the equipment selection and installation, that components have the adequate reliability to reduce mechanical failures.

Finally, the studying of the taxonomy allows identifying those accidents that are more likely to occur or that repeated with more frequency. This will help to focus resources and obtain a more efficient solution in its mitigation or prevention.

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