Risk Analysis and Indentification of Environmental Impacts Associated with Hydraulic Fracturing in Shale Gas Production

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The production of shale gas in Brazil has great potential to meet the country's energy needs. This process uses hydraulic fracturing, which is a good stimulation method, that induces fractures in the reservoir rock by injecting a fracturing fluid into it. Therefore, it permits increasing the permeability around the well, and the well's productivity index. It is crucial to understand the operation and the factors influencing the process to mitigate the risks involved in hydraulic fracturing. This work aims to identify and analyze the possible failure modes and their risks through risk analysis methods [Failure Modes and Effects Analysis (FMEA), and Fault-Tree Analysis (FTA)], in addition to connecting them to environmental impacts. We expected that this integrated method would support the safe monitoring of the technique in the future.
Keywords: Fracking. Shale Gas. FMEA. FTA. Environmental Impacts.

Introduction

With the increase in global energy demand, the search for alternative resources has become an increasingly necessary reality. In Brazil, with the reheating of onshore field activities, there is potential for the exploration and production of unconventional gas in onshore basins, such as those in the Recôncavo Baiano, São Francisco, Sergipe-Alagoas, Parnaíba, Parecis, Paraná, Potiguar, Amazonas and Solimões [1,2].

Located in low permeability reservoirs, shale gas is exploited using the hydraulic fracturing technique, which consists of creating fractures through the reservoir rock by injecting a fracturing fluid under high pressure, leading to increased permeability in the rock and, consequently, increasing the productivity rate of the well [3,4].

The method's objective is to increase the permeability and porosity of the rock by fractures, which propagate through the rock formation, to facilitate the extraction of oil or gas. Before fracturing occurs, vertical drilling takes place to a depth of approximately 1.2 km to 3.6 km; reaching the kick-off-point (KOP), horizontal drilling begins, up to 1.2 km in length [5], to reach a larger area to extract as much oil or gas as possible. After the drilling phase, the horizontal section is fractured with the injection of chemical fluids and a high amount of water at a pressure that is higher than the fracturing pressure (5,000 psi), together with thickeners that act as support agents (sand, polymeric gums, and silica) that create a preferential path of high conductivity, facilitating the fluid flow [4].

Considered high risk, the technique is not well regarded by a part of society as it is associated with the possibility of environmental and social impacts, such as aquifer contamination, and geological risks, among other negative impacts, depending on the conditions in which it is practiced [6,7]. However, the Brazilian potential with its reserves makes an intensified effort and studies the efficiency of hydraulic fracturing for the exploration and production of shale gas and the control of its impacts favorable for the country [8,9]. In addition, the country could double its gas reserves if only 10% of the gas were commercially viable.

The use of hydraulic fracturing in Brazil requires greater knowledge about the real risks and impacts present depending on the characteristics

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of the reservoir, seeking to minimize failures and mitigate the environmental and social impacts arising from this practice [10]. Lima and Gonçalves [11] emphasize the need for technical knowledge about the method, to improve it, better monitor the fracture process, and minimize damage to the environment in the recovery of gas in shale gas type reservoirs. Thus, environmental studies on the impacts of hydraulic fracturing are important as they allow for the subsidizing of eventual licenses concessions by environmental agencies. Therefore, it is necessary to know the characteristics of the Brazilian aquifers and the petrophysics and geomechanics of shales [6].

The risk analysis of the shale gas production process through Hydraulic Fracture will be performed using the FMEA (Failure Modes and Effects Analysis) and FTA (Fault-Tree Analysis) methods [12]. The FMEA method is used essentially for preliminary evaluations to increase the knowledge about the functioning and performance of the studied systems by identifying the main issue in the process. Consequently, after identifying and solving the problem, there is a reduction or even cancellation of failures. The FTA Analysis method, on the other hand, is applied to carry out a systematic approach that allows identifying the root of a problem through a diagram. One of the differences that have become a complement to the FMEA method is having the ability to map a series of events until the possible causes that originated the failure are reached, that is, a correlation between failures and subsystems.

In this way, it is possible to identify failures and their severity, frequency of occurrence, probability of detection, priority problem, and their causes from the combination of methods. Therefore, they are methods that seek to improve the quality and assertiveness of the process, making it safer and more reliable.

The production of shale gas can lead to operational failures due to the extreme conditions of the process, compromising operational safety due to risks related to environmental impacts. Therefore, there is a need to understand how the fracturing mechanism occurs and what are the environmental impacts involved during this type of operation.

The objective of this work is to carry out a preliminary survey of the failure modes of hydraulic fracturing, which can occur during the fracturing stages of reservoir rock and gas production. It will be possible to identify and analyze possible risks of the interaction of hydraulic fracturing mechanics with the geological environment of the unconventional reservoir through the use of risk analysis methods FMEA and FTA, in addition to correlating the risks to their possible environmental impacts.

Materials and Methods

This study has a predominantly exploratory character, with its development based on data and information obtained from bibliographic references. Google Scholar and Science Direct databases were used on a query basis, from 2017 to 2021. Through strings such as fracking, shale gas, risk analysis, and environmental analysis, we searched for papers that associate the mechanism of hydraulic fracturing with environmental risks and impacts arising from its activity. Understanding the environmental aspect (cause) arising from the interaction of an element with the environment brings as a consequence the impact of this activity. A methodological proposal for this work involves the following steps: (i) study the hydraulic fracturing technique; (ii) identify the variables that influence the process; (iii) identify and associate environmental risks and impacts; and (iv) verify the potential application of FMEA and FTA risk analysis techniques.

Failure Modes and Effects Analysis - FMEA

The FMEA methodology was used to analyze the risks involved in the Hydraulic Fracture process to show the problem to be solved that is a priority. This priority problem is found through a Risk Matrix that contains the Risk Priority

Number - RPN, in which the higher the number, the more critical the failure in question and the faster a measure or action should be taken to avoid it. The RPN is calculated using Equation 1.

$$RPN = G \, x \, O \, x \, D \quad (1)$$

Where:
G - Severity; O - Probability of Occurrence;
D - Probability of Detection.

The “G” and “O” elements are scored from 1 to 10 following the logic of 1 for very low and 10 for very high severity or probability of occurrence, whereas in “D” 1 is for high detection probability and 10 for low probability.

Fault-Tree Analysis - FTA

Another risk analysis method is the FTA, which aims to identify the root of the problem/fault with the highest risk score (RPN), i.e., the priority problem analyzed in the FMEA method. The analysis occurs through the assumption of causes for that failure. So, it is possible to exclude reasons for the occurrence of the problem, which facilitates its identification and subsequent remediation, and consequently, the occurrence of failure can be canceled. The method analyzes the failure modes with the highest RPN of each risk matrix, following the FMEA technique.

Results and Discussion

From the databases consulted, the interactions between the key terms fracking shale gas risk analysis and environmental analysis were tested. From the set of researched works, we noticed a lack of studies that associate risks and environmental impacts arising from the use of the hydraulic fracturing technique in the production of shale gas. Thus, the need for this type of approach stems from the importance of establishing the relationship between cause (failure mode) and effect (environmental impact) with the use of the technique. Although preliminary, the results that will be presented in this work contribute to adapting the proposed methodology to identify and assess the environmental risks and impacts of the production of shale gas.

In the course of hydraulic fracturing, problems can occur that affect the integrity of the activity and, consequently, cause environmental and social impacts. Initially, a preliminary assessment of the operational characteristics of hydraulic fracturing was carried out under the conditions of the reservoir, which allowed the identification of possible failure modes of the process and their risks, which are capable of causing potential environmental impacts (Table 1).

From Table 1, it was possible to identify the main risks associated with the hydraulic fracturing technique, which are the cause of unwanted fractures and the occurrence of fracturing fluid or gas leaks. Therefore, as proposed in the method, the risk analysis technique (FMEA) was used to analyze these main risks presented in Table 1, so that from this analysis it is possible to identify the failure mode with the highest RPN value, which demonstrates the problem that is a priority to be solved.

First, there is the risk analysis of the cause of unwanted fractures (Table 2). Unwanted fractures are those caused accidentally, which occur with the loss of control over the pressure that the fluid exerts on rock formations, only in the situation where the upper capping rock has lower minimum stress than that of the lower capping rock, there is a possibility of environmental impact since the flow of the fracturing fluid would go towards the surface, reaching existing groundwater and contaminating it.

The failure modes analyzed were: I) Exceeding the fracture pressure continuously; II) Deviation in the geomechanical study of the reservoir; III) Uncontrolled spread of the fracturing fluid.

The fracture pressure (Pf) is calculated through a geometric correlation that proportionally relates to the pressure gradients of the depth that will be fractured. Thus the reference value of Pf is obtained, and so a Pa greater than Pf is applied

Table 1. Failure modes x risks x environmental impacts.

Failure Modes	Risks	Environmental Impacts
Continuously exceed fracture pressure	Cause unwanted fractures to groundwater	Contamination of groundwater and subsoil
Deviation in the geomechanical study of the reservoir	Cause unwanted fractures to groundwater	Contamination of groundwater and subsoil
Uncontrolled spread of fracturing fluid	Cause unwanted fractures to groundwater	Contamination of groundwater and subsoil
Well cementing failure	Occurrence of fracture fluid or gas leaks	Increased concentration of toxic gases in the atmosphere Contamination of groundwater and subsoil
Piping corrosion	Occurrence of fracture fluid or gas leaks	Increased concentration of toxic gases in the atmosphere Contamination of groundwater and subsoil

Table 2. Risk matrix cause of unwanted fractures.

	Cause of unwanted fractures				
	Fail Mode	G	O	D	RPN
1	Continuosly exceed fracture pressure	8	4	3	96
2	Deviation in the geomechanical study of the reservoir	7	5	6	210
3	Uncontrolled spread of fracturing fluid	9	4	5	180

to open the fractures. However, once the fractures are opened, Pa is gradually reduced and an irregular fracture doesn't occur. On the other hand, the geomechanical study of the reservoir aims to provide prior knowledge of the rock's properties, especially its permeability, porosity, temperature, and compressibility. All this data and the proximity to some groundwater are extremely important, since, as they are estimated, an error in the calculations or the studies can cause serious environmental impacts. Lack of control in the propagation of the fracturing fluid is another failure mode, which can occur due to the existence of natural fractures in the reservoir. There is the possibility of an involuntary connection of a fracture caused by the process with a natural fracture to happen and so, with the application of the fluid of fracturing in these unforeseen sites, it is possible that new fractures would be opened, which is unwanted.

Subsequently, the risk analysis of the occurrence of fracturing fluid or gas leaks was carried out, Table 3, of which the failure modes analyzed were: I) Failure in cementing the well; II) Piping Corrosion.

In the same way as the fracturing fluid, the gases present in the reservoir rock or those from the production itself can also migrate to the surface due to a difference in density, causing the contamination of groundwater and an increase in the concentration of toxic gases in the atmosphere.

The irregular cementation of a well is one of the biggest concerns regarding the integrity of the well. This failure can be described as a poorly done zonal isolation, which if not identified or controlled, can give rise to accidents that cause personal, material, environmental and financial damage. Due to the practice of operations to avoid failures in cementing the well, its probability of

Table 3. Risk matrix occurrence of fracture fluid or gas leaks.

	Occurrence of fracture fluid or gas leaks				
	Fail Mode	G	O	D	RPN
1	Well cementing failure	9	4	5	180
2	Piping corrosion	7	5	4	140

occurrence is minimized, however, it still exists. Unlike cementing failure, piping corrosion, a process of deterioration of the internal surface of the well, is more likely to occur. In addition to harming the process, it delays the production operational schedule, generates high maintenance costs, and can also generate health risks and the environment.

After performing the risk analysis using the FMEA method, it is possible to identify the failure modes with the highest RPN. The results showed that “Deviation in the geomechanical study of the reservoir” and “Failure in cementing the well” are the problems to be solved as a priority, concerning the risk matrices in Table 2 and Table 3, respectively. Thus, it appears that the steps with the greatest possibility of causing environmental impacts are those linked to the characteristics of the reservoir, the good profile, and the injection of fracturing fluid.

After identifying the priority failures, another risk analysis was carried out, FTA, which should present the possible causes for the occurrence of the failure that will be analyzed. Thus, it was possible to build the fault tree for each problem mentioned, as can be seen in Figure 1. Through this analysis, it is possible to identify the causes of a deviation in the geomechanical study of the reservoir. One of the main reasons is the inadequate choice of the fracture model, which can occur due to an error when estimating the reservoir properties since they are performed through computational tests, which means that they are not exact. Just as the reservoir properties are not accurate, the two-dimensional and three-dimensional fracture models are not either. Therefore, due to the imprecision of the fracture models and the estimation of reservoir properties, there is a possibility of a deviation in the geomechanical study of the reservoir, which may cause unwanted fractures that can cause serious environmental impacts.

The FTA for “Cementation Failure” was also constructed (Figure 2).

From the analysis carried out, it can be seen that “Cementing Failure” has several causes to be analyzed, which may explain its greater severity and higher difficulty of detection of “Piping corrosion”. The main cause of this failure can be contamination of the cement slurry, so the cement properties are altered due to interaction with the drilling fluid, which impairs the cementation of the well. There is also the possibility that the volume of the cement paste was insufficient, due to loss of circulation, which would be the invasion of fluid for formation through natural or induced fractures or in depleted formations. This can also occur due to some break-in in the well, which would lead to an unexpected increase in the diameter of the well. Furthermore, choosing a cement of a quality that meets the requirement of high shear strength is extremely important, as the cement's adherence to the good wall is crucial for efficient cementation.

Conclusion

After the risk analysis is performed on the possible failure modes arising from the fracturing and gas production steps, it is concluded that the integrated methods of FMEA and FTA, when used together, are able of providing sufficient data on the possible risks of using the Hydraulic Fracture technique in shale gas exploration and production. Even though a preliminary study, it is possible to identify the presence of environmental impacts such as groundwater contamination and increased concentration of toxic gases in the atmosphere.

Figure 1. FTA of the Deviation in the geomechanical study of the reservoir.

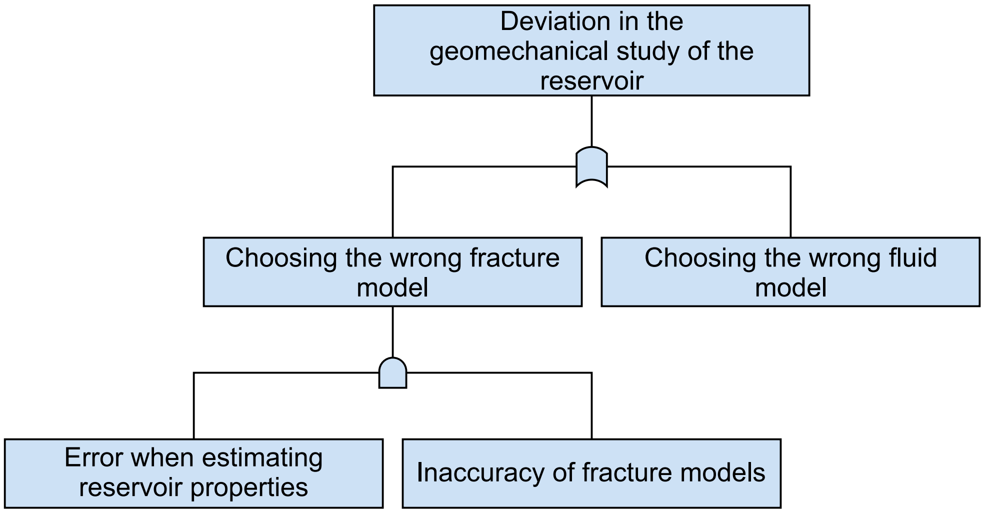
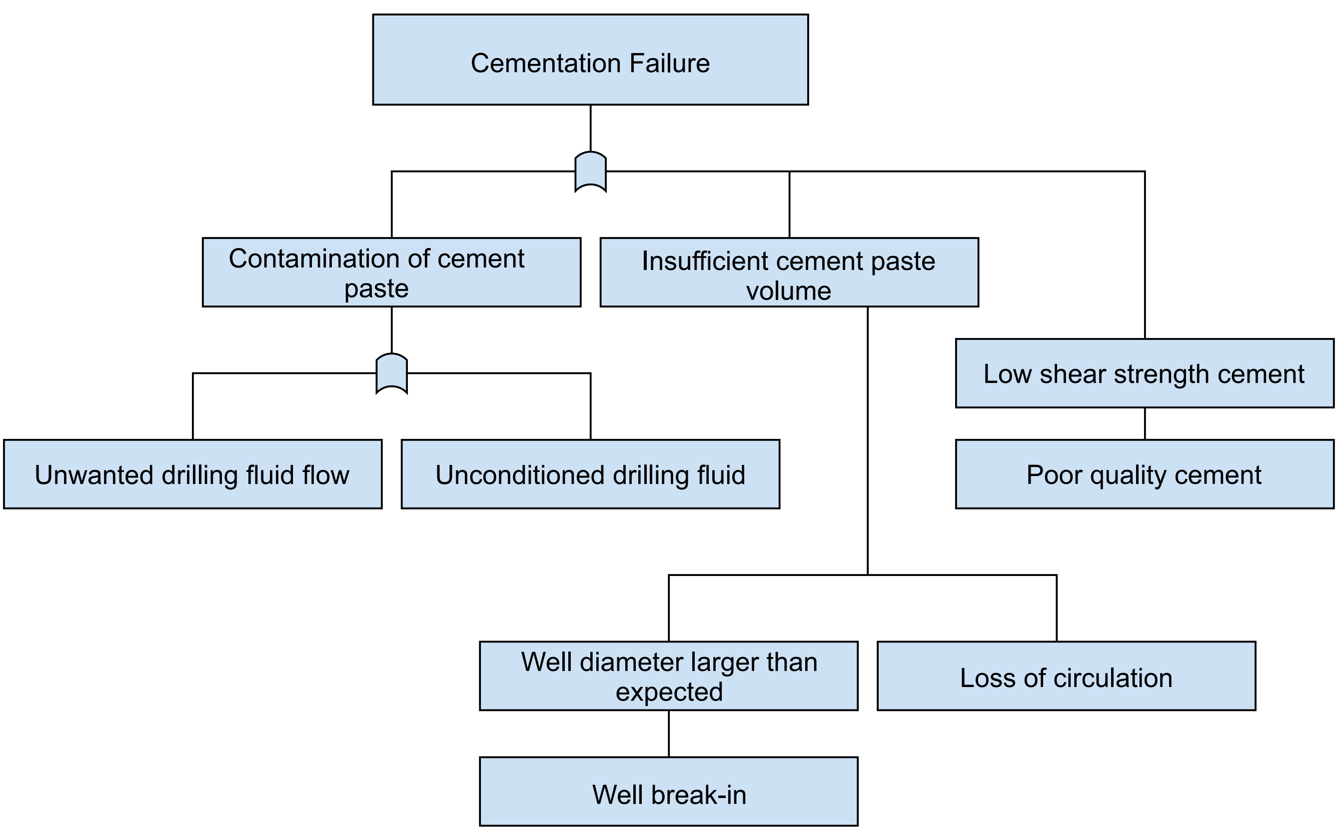


Figure 2. FTA of Failure to cement.



However, it is expected that with more studies in the future, based on more detailed risk analysis, it will be possible to reduce possible risks, through fracture monitoring or the application of more accurate fracture modeling software. From this, the probability of the occurrence of environmental impacts would decrease, so that the applicability of the technique would become safer and more reliable, so that, in the future, such a proposal will be able to offer greater incentive to the exploration and production of oil and gas in unconventional reservoirs, to take advantage of the energy potential available in the country.

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