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Article

Risk Assessment of Selected CCS Wells through Feature, Event, and Process Method and Comparison of the Barrier Effect

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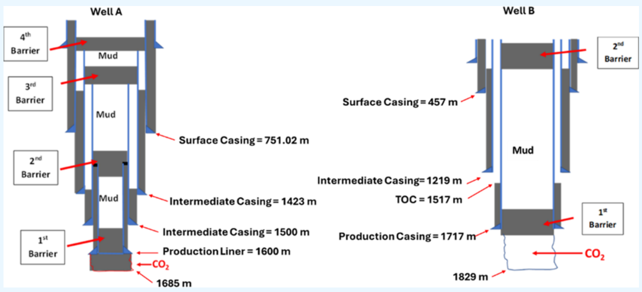

ABSTRACT: To reduce the CO_2 release in the atmosphere, the carbon capture and sequestration (CCS) technique presents a solution in which the CO_2 is captured from the emitting source and injected into a suitable geological formation in the subsurface. For the CCS project to be successful, CO_2 must be trapped underground for hundreds of years. In that respect, good integrity plays an important role as it ensures that the injected CO_2 remains sequestrated in the subsurface. Hence, this study presents a risk assessment technique with the help of which critical elements that can compromise the integrity of the CCS well can be identified. The approach taken for the risk assessment is based on the feature, event, and process (FEP). However, this method gives a qualitative analysis, and to convert it to a semiquantitative one, FEP is integrated with an interaction matrix, incident potential matrix (IPM), and cause−effect plot diagram. In this paper, risk assessment was conducted on two fictitious wells with different well configurations. It was found that cement and casing were the most vulnerable components, while formation water and subsidence were the most problematic elements in the given well system. It was also concluded that the number of plugs and their location in the well could increase or decrease the intensity of the risk levels in the CCS wells.

1. INTRODUCTION

Many countries have set a net zero goal to reduce the emissions of CO_2 in the atmosphere. As reported by Rao et al.,[1] the contribution of carbon dioxide to greenhouse gases is about 72% and is one of the leading causes of global warming. International Energy Agency (IEA)[2] reports that the emission of CO_2 into the atmosphere increased by 1.7% by 2018, corresponding to an increase in the concentration of CO_2 to 407.4 ppm. In 2020, about a 5.8% decrease in CO_2 emissions was recorded, and the main reason behind this was the pandemic, which shut off many energy sectors. However, as the world returns to its normal operation, the energy demand will increase, increasing the level of CO_2 emissions in the atmosphere. It is reported by Cao et al.[3] that about 78% of the energy demand will be fulfilled by fossil fuels to meet the energy demand in the coming future. Keeping this in view, different strategies are devised to control the release of CO_2 into the atmosphere, such as the use of renewable energies, energy conservation, population control, clean fuel, and energy-efficient technologies. However, one of the biggest strategies that can be used without disturbing the country's economic growth is carbon capture and sequestration (CCS).[4] The concept of CCS was put forward in 1977 when CO_2 from a coal power plant was collected and injected into the subsurface.[5] CCS is a collection of different operations in which the CO_2 is captured from the emission source and then transported to the location where the CO_2 is injected into suitable geological formations. It is important to note that old oil and gas wells can be reused from the CCS projects. As many abandoned wells can become an economic burden on the government or operator in the long run, these wells can be converted to CCS wells. However, it is crucial to check the risk assessment on the wells before the conversion to ensure that the CO_2 injected in the subsurface remains there for hundreds of years and is not leaked to the surface. Moreover, the risk assessment criteria should include all of the scenarios in the case of leakage of CO_2 to the surface.

Different studies have conducted CCS risk assessments, which are discussed in this section. The study conducted by ATLANTIC[6] presented the risk assessment framework for the containment of CO_2 in the subsurface. In their studies, 6 risk

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Table 1. Literature Review of the FEP for Radioactive Waste Material Disposal

country	organization	used for	number of FEPs	refs
	International Atomic Energy Agency (IAEA)	scenarios related to the release of waste repositories	60	17,18
	IAEA BIOMOVS II	international BIOsphere model validation study—phase II	140	22
	CEC	CEC everest project	10 IIE (independent initiating events) was developed that led to additional scenarios in different lithologies, which were 5 in granite, 7 in salt, and 7 in clay	23
Canada	Atomic Energy of Canada Ltd. (AECL)	disposal of nuclear waste at near-surface	150	24
Canada	AECL	disposal of waste from CANDU reactor in granite caverns	280	25
Spain	N/A	disposal of nuclear fuel in the deep crystalline rock formation	120	26
Netherlands	ECN/RIVM/RGD	disposal of nuclear waste in salt formations	130	27
Sweden	Swedish Nuclear Fuel and Waste Management Company (SKB)/Swedish Nuclear Power Inspectorate's (SKI)	waste nuclear fuel stored in copper canisters and buried in bedrock	160	28
Sweden	SKB	the geological barrier of the buried nuclear waste	150	29
Sweden	SKB	assessment made for site 94 and Aspo site	165	30
United Kingdom	Department of Energy (DoE)/Her Majesty's Inspectorate of Pollution (HMIP)	disposal of mid- and low-level wastes in volcanic rock	300	31
United Kingdom	HMIP	disposal of midlevel waste in volcanic rock	80	32
USA	Sandia National Laboratories (SNL)/Department of Energy (DOE)	assessment of the geological formation after the disposal of nuclear waste	30	19
USA	DOE	disposal of transuranic waste in the salt bed	240	33
USA	DOE and SNL	for the waste-integrated performance and safety code (IPSC)	208	34
Switzerland	Nagra	radioactive waste disposal in the crystalline basement	240	21,35
South Korea	Korea Atomic Energy Research Institute (KAERI)	scenario related to the release of radionuclides in the close geological formation	5 major categories have been further divided into representative FEPs	36

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assessment stages were proposed but did not explain how the information in each stage can be evaluated.[7] The qualitative risk assessment on the field of Goldeneye was conducted by Tucker et al.[8] in which the Bowties diagram approach was utilized. They found that the risk of CO_2 leakage in the given field was very low. However, they neglected two crucial parameters: caprock leakage and CO_2 interactions. He et al.[9] used the Bayesian network (BN) to assess the risks associated with injected carbon dioxide (CO_2) into carboniferous formations for storage purposes. They highlighted the importance of a comprehensive risk assessment and management to ensure the safety and efficacy of CO_2 storage in carboniferous formations. Govindan et al.[10] utilized a numerical approach to assess the risk for the Ketzin site in Germany and presented the CO_2 plume map distribution in the reservoir over different time periods. A detailed review of the risks associated with HSE (Health, Safety, and Environment) was presented by Li and Liu.[11] A numerical program was given by Alcalde et al.[12] for the integrity of the CO_2 storage site for the time scale of 10,000 years. They concluded that the moderate well density leakage rate was below 0.0008% per year, with 98% of the injected CO_2 trapped in the subsurface. An in-depth analysis of various risk assessment and management strategies associated with carbon capture and geological storage was conducted by Larkin et al.[13] Their main focus was on the CO_2 injection and its storage; however, critical components in the well, such as cement or casing that control the integrity of the well, were not considered. Xiao et al.[14] presented a quantitative risk assessment on the leakage of CO_2 and brine in the groundwater of the Farnsworth unit, Texas. A probabilistic risk assessment was performed to quantify the risks to groundwater quality. The authors documented the presence of small amounts of arsenic and selenium adsorbed onto clay minerals. They proposed that monitoring pH levels of groundwater could be an early detection method for detecting potential leakage of CO_2. The study conducted by Brown et al.[15] integrated the qualitative and quantitative risk assessment methods in the context of carbon storage, using the quest carbon capture and storage facility as a case study. Qualitative methods such as hazard identification and scenario analysis were combined with quantitative techniques such as probabilistic risk assessment and Monte Carlo simulation. By integrating these approaches, they presented a comprehensive framework for evaluating and mitigating risks associated with carbon storage projects. The shortcoming of this study was that it did not cover all of the risk scenarios related to the leakage of CO_2 in the CCS field. Hence, in that respect, feature, event, and process risk assessment techniques play an important role that considers all of the scenarios related to CO_2 leakage. Generic FEP databases presented by Quintessa[16] for CCS are not tailored to any specific CO_2 storage concept or location. Instead, they serve the following general purposes:

- Aid in the structured development of models and scenarios for CO_2 storage. The FEP databases provide a comprehensive framework to consider the relevant factors that could impact CO_2 storage performance.
- Act as an audit tool to evaluate the completeness and accuracy of scenarios and models.
- Provide knowledge bases and reference information to support various CO_2 storage research and assessment studies.
- Stimulate discussions and knowledge sharing among experts working on CO_2 storage projects and evaluations.

In essence, these generic FEP databases by Quintessa[16] are designed to be broadly applicable, serving as comprehensive checklists and frameworks to systematically identify and consider the important factors that can influence the safety and efficacy of geologic CO_2 storage without being tied to any specific storage site or project. This helps ensure a thorough and structured approach to the CO_2 storage assessment and risk management. Therefore, this study uses the FEP to assess different CCS well configuration risks and integrates them with the interaction matrix, incident potential matrix, and cause–effect plot diagram, which will be explained in Section 2.

FEP is not a new risk assessment technique and has been used since the 1980s for risk assessment of radioactive waste disposal in the subsurface. The International Atomic Energy Agency (IAEA)[17,18] outlined approximately 60 potential phenomena associated with various scenarios for radioactive waste repositories. Meanwhile, Sandia National Laboratories (SNL) in the United States compiled 30 potential disruptive processes and events for the disposal of transuranic waste in salt beds, forming the foundation for initial scenario development studies.[19] Additionally, in Europe, a framework titled "Twenty-five primary events" was established for probabilistic assessments concerning the disposal of radioactive waste in clay beds, utilizing fault tree methodology as its basis.[20] In the Swiss project, Gewähr curated a catalog of events and processes associated with the disposal of high-level waste in crystalline basements.[21] These initiatives marked the inception of FEPs, inspiring numerous countries to develop their own FEP frameworks for underground radioactive waste disposal, as shown in Table 1.

Following the same concept of the FEP for radioactive waste, the FEP for the CCS was created, and different studies were conducted. The risk assessment on the Illinois Basin–Decatur Project (IBDP) was made to assess the impact of the CCS project on the environment, economics, health, safety, research, and industry stewardship.[37] The study's main goal was to monitor the behavior of injected CO_2 (2 million metric tons) in the subsurface (2150 m). The risk assessment approach was from the feature, event, and process (FEP), in which 123 FEPs were initially evaluated and 88 different scenarios were made from it. It was concluded that the risk must be re-evaluated before any new activity starts and when sufficient data is collected.

The risk assessment on 1424 CCS wells was conducted by Duguid et al.,[38] in which they assessed the likelihood and severity of the CO_2 leakage from these wells. In that respect, they used 13 different categories for likelihood, while four categories were utilized to demonstrate the severity. The most common risk associated with the leakage of CO_2 from the CCS well was from the cement, casing, and well type. Moreover, the presence of formation water and its distance from the wells dictated the risk ranking of the wells. Condor and Asghari[39] presented the concept of FEP linked to the interaction matrix to assess the risk assessment of the CCS well under consideration. Different risk values were assigned to each box of the interaction matrix according to the severity and likelihood of the elements interacting with each other.

The risk assessment that will be discussed in this paper is based on the feature, event, and process (FEP). The generic

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database for the CCS FEP analysis is taken from Quintessa[16] and was applied to the fictitious wells. The FEP included in the database deals with the long-term safety performance of stored CO_2 in the subsurface layers after injection. Features are defined as the static factors and parameters that describe the storage system of CCS (faults, unconformities, caprock, etc.). Processes are all surface and subsurface processes that describe the current and future physical, chemical, and biological dynamical aspects of sequestration, like seal failure, creep, erosion, and deposition. Events are future changes of features and processes or potential occurrences, e.g., earthquakes or blowouts. The FEPs assist in identifying release scenarios by different storage system elements (casing, cement plug, water chemistry, etc.). There are almost 200 FEPs in the Quintessa database that are divided into eight categories, which are further subdivided into subcategories. The main division of the FEPs is as follows:[16]

1. The assessment basis:
   it dictates the boundary condition of the assessment to be made. It helps in screening out the FEPs that would not be considered in the well system under consideration.
2. The external factors:
   it deals with human and natural factors that are beyond the system domain. These FEPs are more concerned with scenarios that relate to the future evaluation of the system.
3. The CO_2 storage: i
   t relates to the pre- and postclosure consideration or assumption of the system
4. The CO_2 properties, interactions, and transport: t
   hese FEPs deal with the fate of the captured CO_2 in the subsurface. The phase behavior and properties of CO_2 can change according to the porosity, permeability, temperature, depth, and pressure in which it is stored.
5. The geosphere
   : FEPs of these criteria deal with the storage site's hydrology, geology, and geochemistry. It gives information about the natural system of the storage site before the injection of the CO_2.
6. Boreholes: i
   t deals with the change of natural systems due to human intervention, such as drilling the borehole. These FEPs also give the long-term performance of the storage site with the plug and abandonment of the wellbore.
7. The near-surface environment: i
   t deals with the FEPs related to the scenarios in which the stored CO_2 comes to the surface and is in contact with human life. The environment can be marine or terrestrial, and the behaviors of the humans in the particular environment have to be described.
8. The impacts:
   these FEPs tell about the end point of interest concerning safety and performance. The impact can be on flora, fauna, humans, or the ecosystem.

As seen from the above division, many categories of FEPs are present. However, parameters 1, 2, 3, 4, 5, 7, and 8 will be the same for the wells of the same field, whereas 6, which deals with the borehole, will be different for the wells of the same field. The well completion and condition of cement or plugs can be different from each other. The FEP related to the borehole is as follows:

- Formation damage (feature)
- Well lining and completion (feature, process)
- Workover (feature)
- Monitoring well (feature)
- Well records (feature)
- Closure and sealing of borehole (feature)
- Seal failure (process)
- Blowouts (event)
- Orphan wells (feature)
- Soil creep around borehole (process)

The limitation of the FEP is that it can give only a qualitative risk assessment. To show the relation of one FEP with the other, two techniques can be utilized. The first one is the use of a process influence diagram (PID). However, the drawback of this method is that it only gives a qualitative assessment and is considered a simple visual method that assists in understanding the different parameters of the FEPs with each other.[16] The other method that will be the focus of the paper is the interaction matrix integrated with the incident potential matrix (IPM) and the cause−effect plot diagram. The benefit of using such an approach is that the FEP (qualitative) risk assessment can be converted to a semiquantitative analysis and can assist in evaluating which component in the given well system is vulnerable to failure. Therefore, this paper presents fictitious wells with different well configurations, and their risk assessment is made with respect to FEP, interaction matrix, IPM, and cause−effect plot diagram. It must be noted that the risk assessment made in this study is specific to the well system considered in this article and is not a general FEP that can applied to any CCS well.

2. METHODOLOGY

2.1. Feature, Event, and Process. The first step in the risk assessment is to go through the FEP and select the element(s) suitable for the given well under consideration.

2.2. Interaction Matrix. The interaction matrix is made in such a way that the interaction of one element with the other is written in the matrix columns and rows. An example of the interaction matrix is shown in Table 2. It is worth mentioning

Table 2. Example of the Interaction Matrix

Element 1	*Interaction of 1 to 2* →	*Interaction of 1 to 3*
Interaction of 2 to 1 ↑	***Element 2***	*Interaction of 2 to 3* ↓
Interaction of 3 to 1	*Interaction of 3 to 2* ←	***Element 3***

that it is an asymmetric matrix, which means the interaction of elements 1 to 2 is not the same as the interaction between elements 2 to 1. This interaction matrix is beneficial as it is the first step in changing qualitative risk assessment into semiquantitative. The interaction of the elements is taken from the FEP presented in Quintessa.[16] It must be noted that the interaction matrix size increases with the increase in the elements of the well under consideration. The example shown below has three elements, so the matrix size is 3 × 3. If the

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number of elements increases to five, the matrix size will be 5 × 5.

2.3. Incident Potential Matrix (IPM). IPM is used whenever the risk assessment has to be in a qualitative approach. The risk is defined as the product of the severity and probability

$$\text{risk} = \text{severity} \times \text{probability}$$

In the IPM table, the probability is presented on the y-axis and ranges from A to E, with A being the lowest and E being the highest. Meanwhile, severity is divided into five categories, from ignorable to catastrophic. The IPM is shown in Figure 1,

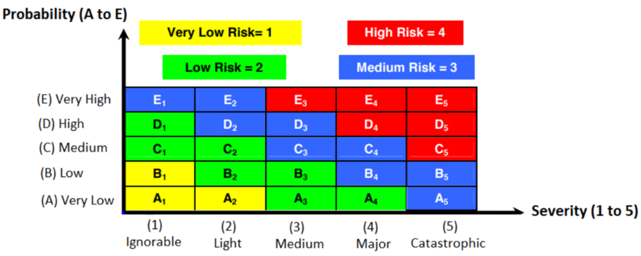

Figure 1. Characterization of the risk level with the help of incident potential matrix (IPM) (Condor and Asghari,[39] Copyright permission granted).

while the description of the risk level is presented in Figure 2. The expert in the given field assigns the risk value to each box in the interaction matrix. Different color codes are provided for better visualization.

2.4. Cause, Effect, Intensity, and Domain. After the values are assigned to the interaction matrix from the IPM, cause−effect calculations are made to help identify the components vulnerable to failure in a given well system. An example in which the risk value is assigned to the interaction matrix is shown in Table 3. After which, the calculation of the cause and effect is made in such a way that the summation of the horizontal row values gives the cause, while the sum of the vertical column gives the effect value. For further confirmation on the component of the well that might be susceptible to failure, intensity and domain can be used, which can be calculated from the following equations[39]

$$\text{intensity} = (C + E) \div \sqrt{2} \tag{1}$$

$$\text{domain} = (C - E) \div \sqrt{2} \tag{2}$$

where

C = value of cause.

E = value of effect.

Table 3. Examples of Interaction Matrix with the Risk Values

	Cause →			
Effect ↓	***Element 1 (1,1)***	*Interaction of 1 to 2* D3 3	*Interaction of 1 to 3* *E4* *4*	***7***
	Interaction of 2 to 1 *A1* *1*	***Element 2 (2,2)***	*Interaction of 2 to 3* *B1* *1*	***2***
	Interaction of 3 to 1 *D1* *2*	*Interaction of 3 to 2* *C5* *4*	***Element 3 (3,3)***	***6***
	3	***7***	***5***	

As seen from Table 4, the most affected element in the given example is element 1, while the element that caused most of the problem in other elements is element 2. This result can also be concluded from the cause−effect plot diagram (Figure 3) in which the component above the mean line is element 2, which shows that this element has the potential of failure, and proper attention should be given to it. While being on the far right side of the graph, element 1 causes most of the problems.

Table 4. Cause−Effect, Intensity, and Domain Value from the Example

Element	Cause	Effect	Intensity	Domain
Element 1 [1,1]	7	3	7.07	2.83
Element 2 [2,2]	2	7	6.36	-3.54
Element 3 [3,3]	6	5	7.78	0.71
Mean	5.00	5.00		

2.5. Work Flowchart. The workflow used in this study is presented in Figure 4. The first part is to select the elements for the given well systems and then go through the relevant FEPs. After which, the interaction of one element with the other will be made in the interaction matrix, and then, the risk value will be assigned by the experts with the help of IPM. In the last stage, the cause−effect diagram is plotted to identify the most critical element in the well system.

2.6. Fictitious Well Description. For this study, two fictitious abandoned wells with different configurations are considered. It is also assumed that these old wells are from the same field, and an injection well will be drilled separately, from

Priority		Description
Nr.	Risk	
A1, A2, B1	Very low	Present interaction cannot be considered in the initial evaluation. But it has the potential of affecting the system.
A3,A4,B2,B3,C1,C2,D1	Low	Important interaction-part of the initial evaluation. Limited or uncertain influence on other parts of the system.
A5,B4,B5,C3,C4,D2,D3,E1,E2	Medium	Very important interaction part of the initial evaluation. They have influence in other parts of the system.
C5,D4,D5,E3,E4,E5	High	Critic interaction – part of the initial evaluation. High probability of influencing other parts of the system.

Figure 2. Description of the risk assessment used in this study (Condor and Asghari,[39] Copyright permission granted).

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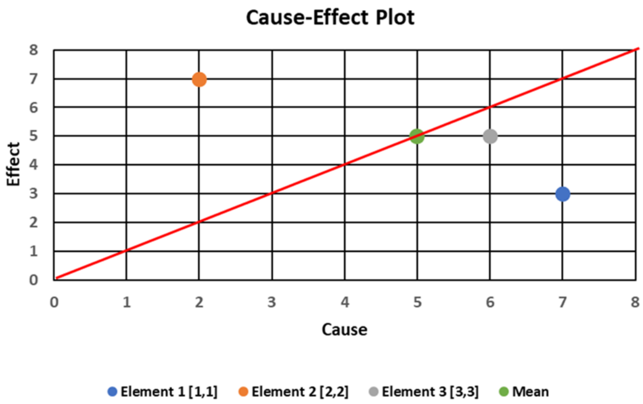

Figure 3. Cause−effect plot diagram from the given example.

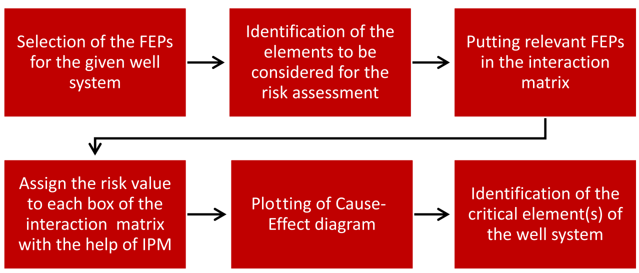

Figure 4. Workflow used in this study for the risk assessment.

which the CO_2 will be injected into the subsurface. Hence, the plume of CO_2 will come to these wells eventually, and the risk assessment will be done to ensure that these will have the capacity to retain the injected CO_2 in the subsurface. The assumed conditions taken for wells A and B are as follows:

- Age of the abandoned wells = 50 years
- Reservoir temperature = 125 °C
- Reservoir pressure after the injection of CO_2 = 24.13 MPa
- Reservoir rock = sandstone
- No CBL (cement bond log) records
- Production casing/liner = carbon steel, N80. Unknown weight (ppf) and connections
- Subsidence at the sea bed = 2 m
- No presence of the H_2S
- Mud placed in between the plug
- Cement type = class G
- Well type = vertical

The configurations of wells A and B are shown in Figure 5. It can be seen that the casings are stubbed at different locations for well A. Meanwhile, in well B, there are no stubs present. Moreover, it can also be observed that the top of the cement (TOC) or cement sheath is always above the casing shoe of the previous casing for well A. In the case of well B, the cement sheath or TOC of the production casing is below the intermediate casing shoe.

In well A, four plugs are placed that act as barriers in the well. In well A, intermediate and surface casings are stubbed, and at those locations, the third and fourth plugs are located. As the cement in well A is not done to the entire length of the casing, the third plugs act as the barrier to restrict the leakage within the intermediate casing and from the annulus present between the two intermediate casings. Meanwhile, the fourth plug restricts the movement of any fluid that tends to leak above the surface casing or in the annulus space that exists between the intermediate and the surface casing, whereas well B has only two plugs, one at the bottom and the other at the top. In this study, a risk assessment will be made on the first and second barriers of these wells, and critical elements in the given well system will be identified.

3. RESULTS

For the quantitative risk assessment of the first or second barrier, the elements of wells A and B are defined, which are as follows:

- Casing
- Cement sheath and plug
- Water composition
- Gas
- Subsidence

Five elements have been selected for the study, so the interaction matrix size will be 5 × 5. The reason for choosing these elements was that the casing and cement are the most important parameters that control the integrity of the well. Water composition and gas were essential for the risk

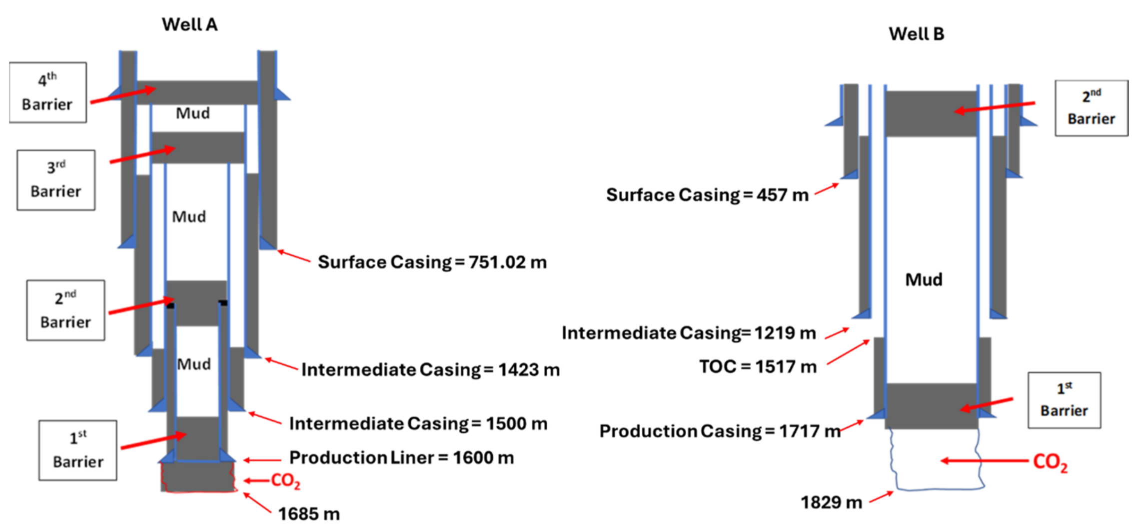

Figure 5. Well A on the left and well B on the right.

Table 5. Interaction Matrix Used in the Wells and Different Barriers

1	2	3	4	5
[1,1] **Casing**	[1,2] (a). Contraction and expansion (b). Debonding (c). Micro annulus (d). Cracks	[1,3] (a). Sorption	[1,4] (a). Flow path (b). Leakage to formation	[1,5]
[2,1] (a). Contraction and expansion (b). Corrosion	[2,2] **Cement sheath and plug**	[2,3] (a). Chemical equilibria (b). Sorption	[2,4] (a). Flow path (b). Micro annuli (c). Mixing with WBM	[2,5]
[3,1] (a). Corrosion b). Erosion	[3,2] (a). Degradation (b). Carbonation and bi carbonation (c). Advection flow (d). Precipitation (e). Buoyancy flow (f) Change in transfer properties	[3,3] **Water composition**	[3,4] (a). Solubility (b). Dissolution (c). Chemical reaction (d). Carbonic acid	[3,5] (a). Mineral dissolution (b). Chemical equilibria
[4,1] (a). Corrosion (b). Erosion (c). Thermal loading	[4,2] (a). Degradation (b). Carbonation and bi carbonation (c). Diffusion (d). Crack. (f). change in transfer properties	[4,3] (a). Dissolution of gas (b). Contaminant transport	[4,4] **Gas**	[4,5] (a). Gas stripping
[5,1] (a). Buckling (b). Compression (c). Bending (d). Shear failure (e). Mechanical loading	[5,2] (a). Debonding (b). Micro annulus (c). Cracks	[5,3] (a). Chemical equilibria (b). Mineral dissolution and precipitation	[5,4] (a). Pressurization (b). Leakage	[5,5] **Subsidence**

assessment because the injected gas, CO_2, can dissolve in the formation water and become a corrosive fluid that can react with the casing and cement, whereas subsidence can significantly impact the cement bonding and casing condition. The interaction matrix for all of the wells and barriers will be the same; however, the risk value will differ due to the well configurations. The interaction matrix made for this study is presented in Table 5.

3.1. Risk Assessment for the First Barrier. The risk assessment for the first barrier of wells A and B will be the same as that of the well lying in the same field. Two different risk assessments are presented for the second barrier. After establishing the interaction matrix, the authors assign the risk value with the help of IPM. Subsequently, a cause−effect plot is made to identify the critical element in the well system. Table 6 shows the risk value in the interaction matrix for the first barrier of wells A and B, while Table 7 presents the cause, effect, intensity, and domain values. Whereas, Figure 6 shows the cause−effect plot diagram.

From Figure 6, it can be noted that cement and casing are the most critical elements that can be prone to failure, as they lie above the mean line, whereas water composition and subsidence cause the most problems in the given well system.

3.2. Second Barrier of Well A. The risk assessment for the second barrier is done because if the first barrier is compromised, then which element(s) can be at risk of failure? It must be noted that the assumption is that the CO_2 leaks from the first barrier and gets dissolved in the mud placed above the first barrier, which can create problems for the elements above the first barrier. The interaction matrix, along with the risk assessment and cause−effect plot diagram, is shown in Tables 8 and 9 and Figure 7, respectively.

In this case (Figure 7), the mean value of the cause−effect is 9.6, which was higher than the first barrier of well A (9.2), and the critical element remains the cement and casing, with cement being above the casing element. Nonetheless, in this case, the water composition creates more problems as compared to the subsidence because the second barrier will be exposed to the leaked CO_2 from the failure of the first barrier to be mixed with the mud that is present between the first and second plugs, creating a harsh environment for the second plug.

The risk assessment of the second barrier of well B is presented in Tables 10 and 11 and Figure 8.

From Figure 8, it can be noticed that the mean value is about 10.5, through which the green line is drawn. It has the highest mean value among all of the cases, as it is the last barrier, and any leak above it will cause the seepage of CO_2 to the surface. Here, the affected value of cement and casing has also increased, as the risk of leakage of CO_2 to the surface has increased substantially, whereas the value of the problematic element also increased with water composition being in front, whose reason has already been discussed previously.

4. DISCUSSION

As seen from the previous section, the first barrier of wells A and B has the same risk assessment as the bottom hole conditions for both wells are the same. It was found that for the first barrier, the most affected element was the cement sheath and then the casing. The elements that cause the most problems are water composition and subsidence. This evaluation is logical as when the CO_2 dissolves in water, it lowers the pH of the subsurface water and creates carbonic acid, which is a corrosive fluid. On the other hand, the subsidence in the well can cause the debonding of the cement from the casing and formation and also deform the casing, creating serious well integrity issues. As for the second barrier of wells A and B, the mean value of the cause−effect increases from the first barrier because the first barrier has already been compromised, which increases the risk level. It was found that the second barrier of well B showed the highest mean value of all of the risk assessments. This is because of the reason that well B is comprised of only two barriers, and if the second barrier fails, then the stored/injected CO_2 will be released into

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Table 6. Interaction Matrix of the First Barrier of Wells A and B

1	2	3	4	5
[1,1] **Casing**	[1,2] (a). Contraction and expansion (b). Debonding (c). Micro annulus (d). Cracks D4 4	[1,3] (a). Sorption A2 1	[1,4] (a). Flow path (b). leakage to formation E4 4	[1,5] N/A
[2,1] (a). Contraction and expansion (b). Corrosion E5 4	[2,2] **Cement sheath and plug**	[2,3] (a). Chemical equilibria (b). Sorption A2 1	[2,4] (a). Flow path (b). Micro annuli (c). Mixing with WBM E4 4	[2,5] N/A
[3,1] (a). Corrosion (b). Erosion B4/C4 3	[3,2] (a). Degradation (b). Carbonation and bi carbonation (c). Advection flow (d). Precipitation (e). Buoyancy flow (f) Change in transfer properties C4 3	[3,3] **Water composition**	[3,4] (a). Solubility (b). Dissolution (c). Chemical reaction (d). Carbonic acid C3 3	[3,5] (a). Mineral dissolution (b). Chemical equilibria A1 1
[4,1] (a). Corrosion (b). Erosion (c). Thermal loading A2 1	[4,2] (a). Degradation (b). Carbonation and bi carbonation (c). Diffusion (d). Crack. (f). change in transfer properties D4 4	[4,3] (a). Dissolution of gas (b). Contaminant transport B2 2	[4,4] **Gas**	[4,5] (a). Gas stripping A1 1
[5,1] (a). Buckling (b). Compression (c). Bending (d). Shear failure (e). Mechanical loading E4 4	[5,2] (a). Debonding (b). Micro annulus (c). Cracks E4 4	[5,3] (a). Chemical equilibria (b). Mineral dissolution and precipitation A1 1	[5,4] (a). Pressurization (b). Leakage A1 1	[5,5] **Subsidence**

Table 7. Cause, Effect, Intensity, and Domain of First Barrier Wells A and B

Elements	Cause	Effect	Intensity	domain
Casing [1,1]	9	12	14.849	-2.121
Cement Sheet and plug [2,2]	9	15	16.971	-4.243
Water composition [3,3]	10	5	10.607	3.536
Gas [4,4]	8	12	14.142	-2.828
Subsidence [5,5]	10	2	8.485	5.657
Mean	9.2	9.2		

the atmosphere, creating serious issues for the environment and humans and will put the success of the CCS project in jeopardy. Moreover, the location of the plug is also an important parameter to consider. It can be seen that the second plug of well B is very close to the surface, and any CO_2 leak from such a plug will have severe consequences, whereas, for well A, multiple barriers are present, and the second plug is placed in the lower section of the well, which lowers the mean value in the cause−effect calculations of the second barrier. Nonetheless, even for the second barrier, the most critical component remains cement and casing. Hence, the condition of these elements must be assured in the abandoned well before the CCS project is started. If any of these elements fails, the integrity of the well can be compromised.

The reason cement is the most critical component is that it readily reacts with carbonic acid, which is formed by the reaction of the formation water with injected CO_2 (eq 3). The solid volume of $Ca(OH)_2$ (portlandite) in the hydrated cement is about 20−25%, whereas C−S−H, the main binding material, occupies 50−60%. The rest of the volume, which will be about 15−30%, consists of ettringite, monosulfate aluminate hydrate, and other impurities.[40] The reaction of the water-saturated CO_2 with the cement starts with the attack

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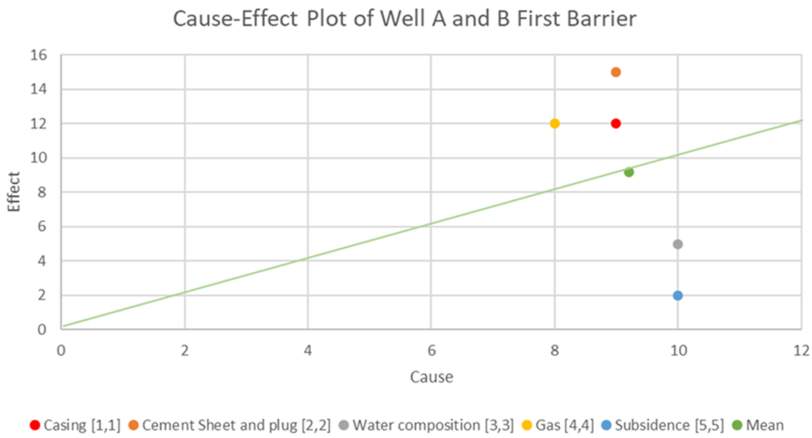

Figure 6. Cause−effect plot diagram of the first barrier of wells A and B.

Table 8. Interaction Matrix of Well A Second Barrier

1	2	3	4	5
[1,1] **Casing**	[1,2] (a). Contraction and expansion (b). Debonding (c). Micro annulus (d). Cracks **E4** **4**	[1,3] (a). Sorption **B2** **2**	[1,4] (a). Flow path (b). leakage to formation **C4** **3**	[1,5]
[2,1] (a). Contraction and expansion (b). Corrosion **E5** **4**	[2,2] **Cement sheath and plug**	[2,3] (a). Chemical equilibria (b). Sorption **A2** **1**	[2,4] (a). Flow path (b). Micro annuli (c). Mixing with WBM **E4** **4**	[2,5]
[3,1] (a). Corrosion (b). Erosion **D3** **3**	[3,2] (a). Degradation (b). Carbonation and bi carbonation (c). Advection flow (d). Precipitation (e). Buoyancy flow (f) Change in transfer properties **E4** **4**	[3,3] **Water composition**	[3,4] (a). Solubility (b). Dissolution (c). Chemical reaction (d). Carbonic acid **D4** **4**	[3,5] a). Mineral dissolution b). Chemical equilibria **A1** **1**
[4,1] (a). Corrosion (b). Erosion (c). Thermal loading **A2** **1**	[4,2] (a). Degradation (b). Carbonation and bi carbonation (c). Diffusion (d). Crack. (f). change in transfer properties **A3** **2**	[4,3] (a). Dissolution of gas (b). Contaminant transport **D4** **4**	[4,4] **Gas**	[4,5] (a). Gas stripping **A1** **1**
[5,1] (a). Buckling (b). Compression (c). Bending (d). Shear failure (e). Mechanical loading **E5** **4**	[5,2] (a). Debonding (b). Micro annulus (c). Cracks **E4** **4**	[5,3] (a). Chemical equilibria (b). Mineral dissolution and precipitation **A1** **1**	[5,4] (a). Pressurization (b). Leakage **A1** **1**	[5,5] **Subsidence**

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Table 9. Cause, Effect, Domain, and Intensity of Well A Second Barrier

Elements	Cause	Effect	Intensity	domain
Casing [1,1]	9	12	14.849	-2.121
Cement Sheet and plug [2,2]	9	14	16.263	-3.536
Water composition [3,3]	12	8	14.142	2.828
Gas [4,4]	8	12	14.142	-2.828
Subsidence [5,5]	10	2	8.485	5.657
Mean	9.6	9.6		

of CO_2 on the portlandite and produces calcium carbonate (eq 5). This process is known as carbonation, which improves the properties of the cement by reducing the porosity and permeability and increasing the compressive strength. However, due to the difference in the pH between the cement, which is alkaline in nature, and acidic formation water, the ingression of the corrosive fluid in the cement continues due to which the carbonate produced in the carbonation process is converted into the bicarbonate, which is easily soluble in water and leaches out of the cement (eq 6). This will lead to increased transfer properties and reduced compressive strength. After the consumption of portlandite, CO_2 starts to attack the main binding material C−S−H and convert it into $CaCO_3$ and silica gel (eq 7). As the molar volume of $CaCO_3$ is lower than that of the C−S−H, the transfer properties in the cement increase further, and mechanical properties decrease, which causes the cement matrix to lose its integrity completely.[40] The reaction of the cement with the CO_2 is as follows[40]

$$CO_{2(aq)} + H_2O \rightarrow H_2CO_{3(aq)} \tag{3}$$

$$Ca(OH)_{2(s)} \rightarrow Ca^{2+}{}_{(aq)} + 2OH^{-}_{(aq)} \tag{4}$$

$$Ca^{2+}{}_{(aq)} + HCO^{3-}{}_{(aq)} + OH^{-}{}_{(aq)} \rightarrow CaCO_{3(s)} + H_2O \tag{5}$$

$$OH^{+}{}_{(aq)} + CaCO_{3(s)} \rightarrow Ca^{2+}{}_{(aq)} + HCO_3{}^{-}{}_{(aq)} \tag{6}$$

$$3H_2CO_3 + Ca_3Si_2O_7{\cdot}4H_2O \rightarrow 3CaCO_3 + 2SiO_2{\cdot}H_2O + 3H_2O \tag{7}$$

As for the casing, it was noted that the reaction of carbonic acid with the casing was not severe. According to Cui et al.,[41] it was found that for specific partial pressures of the CO_2, the corrosion was higher for the sample placed at a lower temperature, i.e., 50 °C, than the sample exposed to a higher temperature of 100 °C. This is due to the fact that the solubility of the CO_2 in the formation water decreases with the increase in temperature,[42] causing the corrosion rate to reduce. On the other hand, if the temperature had been above 150 °C, the corrosion would have been severe in the presence of 1 and 1.5 wt % NaCl concentration.[41] The presence of brine in the subsurface makes the conditions more aggressive toward corrosion of the casing.

The most important outcome of our study is that both wells have the same cause−effect plot for the first barrier, which puts both wells at equal risk. However, when the second barrier was considered, well A showed a dramatic change in the risk due to the presence and location of multiple barriers and ranked better in a risk-based selection process with a mean value of 9.6 versus 10.4. Furthermore, well B relies on casing to preserve integrity, while well A relies on cement.

5. CONCLUSIONS

To make the wells in the CCS project safer, it is essential to conduct a risk assessment to find the critical elements that might be vulnerable to failure. In that respect, FEP integrated with the interaction matrix, IPM, and cause−effect plot diagram helps to identify such components that can create problems during the life of the CCS project. This study shows that the well configuration and bottom hole condition can change the risk level. It is also evident that the well with more barriers will have a lower risk of CO_2 leaking to the surface. Moreover, the location of the plug in the wells can also increase or decrease the risk level.

For the first time, we are proposing the application of the FEP methodology for the wellbore barrier, which can highlight which barrier suffers most in a CCS well and may require workover. In the given fictitious wells, it was found that risk levels increase after the first barrier is compromised. As for the second barrier, well B showed a higher mean value because well B has only two barriers. If the second barrier is also compromised, the injected or stored CO_2 can leak to the surface and impact humans and the environment. It was observed that in all of the assessments, the most critical

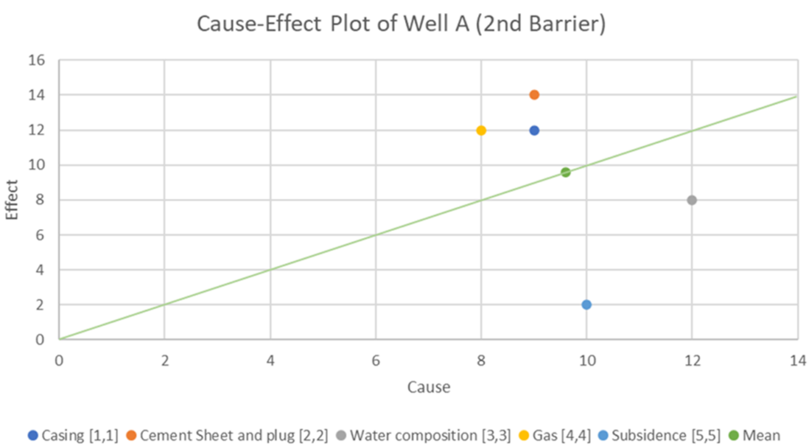

Figure 7. Cause−effect plot diagram of well A second barrier.

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Table 10. Interaction Matrix of Well B Second Barrier

1	2	3	4	5
[1,1] **Casing**	[1,2] (a). Contraction and expansion (b). Debonding (c). Micro annulus (d). Cracks **B5** **3**	[1,3] (a). Sorption **B2** **2**	[1,4] (a). Flow path (b). Leakage to formation **E5** **4**	[1,5]
[2,1] (a). Contraction and expansion (b). Corrosion **E5** **4**	[2,2] **Cement sheath and plug**	[2,3] (a). Chemical equilibria (b). Sorption **A2** **1**	[2,4] (a). Flow path (b). Micro annuli (c). Mixing with WBM **E5** **4**	[2,5]
[3,1] (a). Corrosion (b). Erosion **E5** **4**	[3,2] (a). Degradation (b). Carbonation and bi carbonation (c). Advection flow (d). Precipitation (e). Buoyancy flow (f) Change in transfer properties **E5** **4**	[3,3] **Water composition**	[3,4] (a). Solubility (b). Dissolution (c). Chemical reaction (d). Carbonic acid **C5** **4**	[3,5] (a). Mineral dissolution (b). Chemical equilibria **A1** **1**
[4,1] (a). Corrosion (b). Erosion (c). Thermal loading **A5** **3**	[4,2] (a). Degradation (b). Carbonation and bi carbonation (c). Diffusion (d). Crack. (f). change in transfer properties **A5** **3**	[4,3] (a). Dissolution of gas (b). Contaminant transport **D4** **4**	[4,4] **Gas**	[4,5] (a). Gas stripping **A1** **1**
[5,1] (a). Buckling (b). Compression (c). Bending (d). Shear failure (e). Mechanical loading **E5** **4**	[5,2] (a). Debonding (b). Micro annulus (c). Cracks **E5** **4**	[5,3] (a). Chemical equilibria (b). Mineral dissolution and precipitation **A1** **1**	[5,4] (a). Pressurization (b). Leakage **A1** **1**	[5,5] **Subsidence**

Table 11. Cause, Effect, Domain, and Intensity of Well B Second Barrier

Elements	Cause	Effect	Intensity	domain
Casing [1,1]	9	15	16.971	-4.243
Cement Sheet and plug [2,2]	9	14	16.263	-3.536
Water composition [3,3]	13	8	14.849	3.536
Gas [4,4]	11	13	16.971	-1.414
Subsidence [5,5]	10	2	8.485	5.657
Mean	10.4	10.4		

components in the given well system were cement and casing, while the elements that caused the most problems were water composition and subsidence.

The risk assessment presented in the paper can help to assess the critical components in the CCS wells that might be susceptible to failure so that remedial work can be done on those elements to maintain the well's integrity. However, the limitation of this sort of risk assessment is the risk value given to each box of the interaction matrix, which is mainly based on the experience of the person providing those numbers. To improve the risk assessment and make its prediction more accurate, it is important to conduct long-term testing so that a better risk value concerning likelihood and severity can be given to the individual elements. However, this paper provides

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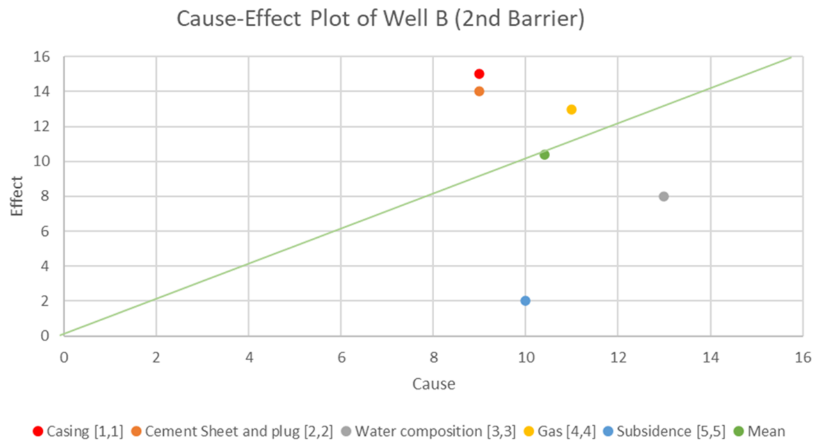

Figure 8. Cause−effect plot diagram of well A second barrier.

a sound basis for understanding the FEP-based risk assessment for young engineers who do not have much experience in the CCS field.

Moreover, it must be noted that the risk assessment made in this study is for specific well conditions and should not be considered a generalized risk assessment that can be used for any CCS wells. The FEPs, elements, and risk values can be changed depending on the condition of the well under consideration.

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Notes

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