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Development of a Risk-Based Approach for High-Sour Exploration Wells

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Abstract

Approximately one-third of the world's gas fields contain 'sour gas', contaminated by hydrogen sulphide, (H₂S)^[1]. H₂S is one of the most deadly hazards in the oil and gas industry, making such fields more difficult to develop, especially when they are located in the vicinity of populated areas. Conventional approaches to wellsite layout generally use conservative consequence-based criteria, which mean a large number of high-sour wells cannot be drilled due to the potential impact on population centres from an uncontrolled release of sour gas. However, adopting a risk-based approach to wellsite layout could change this.

This paper presents a case study in which a Quantitative Risk Assessment (QRA) of a high-sour exploration well was performed to quantify the risk to members of the public from the drilling operation, and ensure that risks were tolerable and As Low As Reasonably Practicable (ALARP). The QRA demonstrated that although the maximum airborne H₂S concentration at the closest populated area would be 60 ppm, the risk levels were assessed as being tolerable and significantly below industry accepted risk tolerability criteria for members of the public. The QRA shows a snap-shot of what can happen but does not demonstrate how the risks are managed in order to prevent the 'one in a million' event from happening. Notwithstanding this, the project team identified a series of further risk reduction measures that were implemented to ensure that the risk to members of the public was ALARP.

The well was subsequently drilled successfully without incident, and the approach described in this paper implemented as the framework for future high-sour exploration drilling operations in the organisation.

Introduction

Drilling for oil and gas has always been an inherently high risk operation, but now that operators are increasingly being required to explore and develop high-pressure high-sour reservoirs to replace their reserves, there are the increased risks associated with hydrogen sulphide (H₂S). As H₂S has adverse health effects at very low concentrations, the consequences of a toxic release from these developments can be seen at significant distances from a drill site. This has implications not only to company employees but also to members of the public.

Most companies have well-established standards for wellsite safety and layout that are applied to new wellsites, new wells drilled at existing wellsites, reactivation of previously abandoned or suspended wells or re-drilling of existing wells such as drilling new laterals or deepening existing wells located in areas that have become populated. Such standards are generally based on relatively conservative assumptions, largely focused on worst-case consequence modelling. This approach is now in conflict with population growth in many Middle East countries. The principal concern for operators is sour oil and gas drilling and production operations in the vicinity of populated areas.

In order for operators to safely explore and develop sour reservoirs, a risk-based approach needs to be implemented to quantify the risk of an uncontrolled release of toxic gas from the reservoir affecting populated areas. A Quantitative Risk Assessment (QRA) has been performed for a high-sour exploration well to show the physical effects (toxic dispersion) of an unconstrained flow from the well. The assessment considers the blow-out frequency, the probability of blow-out type (either vertical/horizontal, with drill pipe/without drill pipe) and the probability of different well fluid types being encountered in the reservoir.

The assessment also lead to a detailed review, using Bow-Tie methodology, of the controls required to be in place to ensure the risks are managed to tolerable and As Low as Reasonably Practicable (ALARP) levels.

The assessment consisted of the following key steps:

1. An assessment of the likelihood of an uncontrolled H₂S release (blow-out) occurring. This was based on review of publicly available data sources^[2] and the author's experience gained from similar projects to assess failure rates. This also included asseswment of the probabilities of different types of blow-outs (i.e. vertical and horizontal and with and without drill pipe);
2. An estimate of fluid type (using offset well exploration results);
3. Computer modelling of near and far field H₂S concentrations that would result from several release scenarios. This utilised FRED modelling software developed by Shell^[9];
4. An assessment of the overall toxic risk using Shell's SHEPHERD software^[10]. The SHEPHERD tool combines the plume modelling results (FRED), local meteorological conditions and the release frequency assessment to quantify the effect and probability of the possible consequences.
5. A Bow-tie (or risk and outcome) assessment to identify: a) the barriers that can be put in place to prevent an uncontrolled H₂S releases; and b) the mitigation measures which can be put into place in order to eliminate or reduce the effects of such a release.

Whilst this paper discussed results relating to H₂S, it is recognised that sulphur dioxide (SO₂) could be produced if the released sour gas cloud was ignited since H₂S is converted into SO₂ during the combustion process. Whilst the assessment did consider SO₂, H₂S was demonstrated to be the main toxic hazard and therefore, the greatest risk. This was because of its primary association in the wellfluids and the higher probability that an uncontrolled release of sour gas would remain un-ignited.

Quantitative Risk Assessment

Quantitative Risk Assessment (QRA) is the means by which the *risk* associated with a hazardous event can be expressed as a function of the hazard's *consequence* and *frequency*. QRA allows for quantifying the risk for a particular concept against risk acceptance criteria, comparison of risk reduction options for a particular hazard in a systematic way, as well as allowing for the comparison of risks resulting from different hazards (e.g. fire, explosion and toxic gas hazards).

The process of QRA includes identification of major hazards, modelling the physical effects (consequences) of hazard scenarios, estimating the frequency of hazard scenarios, and integrating the consequences and frequencies to estimate the risk from a particular hazard. The application of QRA becomes more critical with the increasing risk and complexity of the technologies applied in the oil and gas industry. For example, exploration and development of high-pressure high-sour fields, requires detailed risk assessment of any loss of containment scenario which might result in immediate fatalities.

The method for performing QRA studies is well-documented^[3,4,5,6], hence it is only covered briefly here. In addition, further details on QRA, and QRA limitations and criticalities in high sour hydrocarbon development are provided in Reference 7.

Wellsite Location

The wellsite was in a typical dessert location, but with a settlement 5km from the wellsite and a main road 1.5 km away. Figure 1 shows the wellsite location.

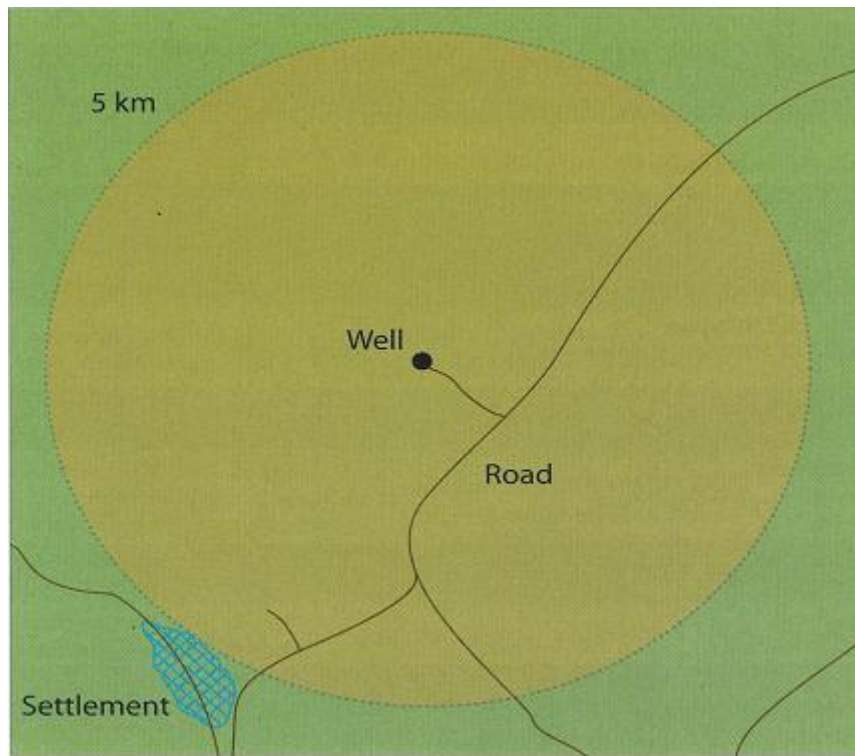


Figure 1: Wellsite Location^[8]

Blowout Frequency

Blowout frequencies were assessed using the Scandpower Report Blowout and Well Release Frequencies (2002)^[2]. Well types were chosen to represent a number of exploration wells seen in the Middle East region.

Although the Scandpower data is predominantly based on information collected in the UK North Sea and the US Gulf of Mexico, it is arguably the most complete and reliable database currently available for blowout data. Therefore, the database was considered adequate for this assessment.

The following frequencies and probabilities have been taken from the Scandpower report:

- Base Frequency of blow-out = 5.3×10^{-5} per year⁽¹⁾
- Probability of blow-out type given blow-out:
 - Outer Annulus = 0.95 (95%)
 - Open Hole = 0.05 (5%)
- Probability of blow-out direction given blow-out
 - Outer Annulus = 49% horizontal & 51% vertical⁽²⁾
 - Open Well = 49% horizontal & 51% vertical

Notes:

- (1) Frequency of blow-out of 5.3×10^{-5} per year refers to the rate which includes all wells drilled in the North Sea and the US Gulf of Mexico.
- (2) The Scandpower report^[2] presents all blow-outs as vertical, however, our experience suggests 49% horizontal and 51% vertical is a more realistic breakdown for onshore drilling operations.

Wellfluid Characteristics

Using local reservoir data, and assessments of similar formations, it was concluded that two fluids could be expected from the exploration well in question. However, the likelihood was for one rather than the other so this was given a 95% probability. The two fluids were:

- Gas Condensate = 95% probability of occurrence
- Oil = 5% probability of occurrence

As the main focus of the assessment was to determine the risks at the settlement (i.e. far field effects), only the gas phase of each wellfluid was modelled. It was assumed that the liquid phase would rain out close to the wellsite.

Release Scenarios

Release scenarios were derived using operational data, documented probabilities and the author's experience. Variables that were considered included:

1. Oil or gas with high H₂S content – derived from experimental data for similar reservoirs.
2. Vertical or horizontal blowout of gas from the well – derived from documented probabilities and the author's experience.
3. Well bore with and without drill pipe in the hole – derived from documented probabilities.
4. Windspeed and direction – derived from site specific data.

Event Tree Analysis

Using the blow-out and well release base frequency derived from the published data^[2] and the probability data detailed above, an event tree was developed. The event tree considered the different potential outcomes associated with a loss of well control event with and without drill pipe in the hole, including horizontal and vertical oriented blow-outs through the annulus and open hole. Figure 2 shows the event tree developed for this analysis. Each scenario on the event tree was modelled for various wind speeds, wind direction and atmospheric stability conditions.

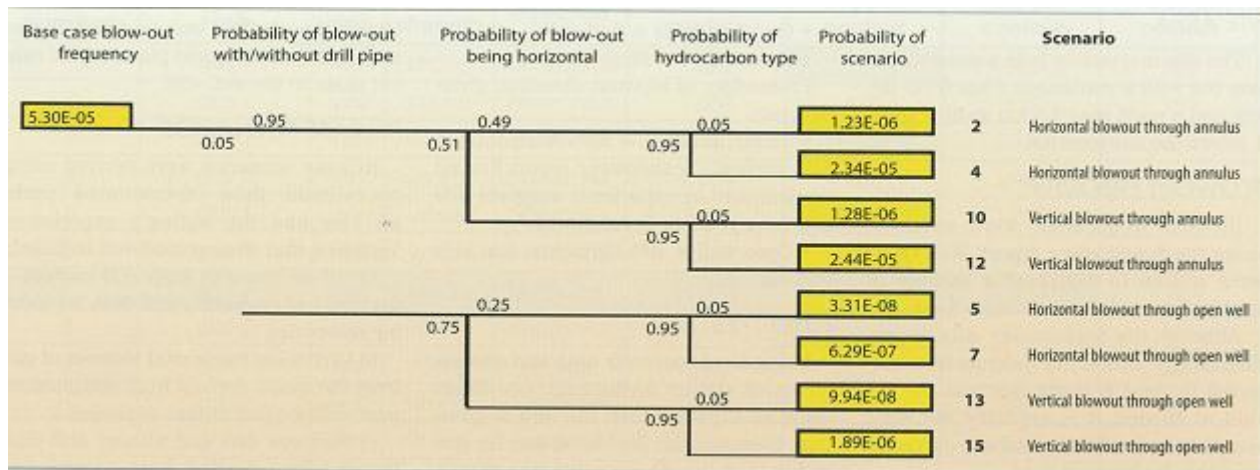


Figure 2: Event Tree Model^[8]

Consequence Analysis

The consequences associated with the different release scenarios defined in the event tree were modelled using the Shell FRED hazard consequence modelling software^[9]. Combinations of the above data lead to the development of the release scenarios provided in Table 1, which represents the full range of possible consequences (or physical effects) for each scenario. The table shows the results of the consequence analysis. It shows that the greatest H₂S dispersion distances are associated with a horizontal blow-out from Gas 2 (oil reservoir), with no drill pipe in the hole, low wind speeds and stable atmospheric conditions. Whilst this scenario results in H₂S concentration in excess of 50ppm at the settlement (5Km distance from the wellsite), H₂S concentrations do not exceed the lethal concentration of 190.66ppm (LC₀₁ for 30 minute exposure)^[11] at this location.

scenario number	hydrocarbon type	drill pipe	breeze strength	direction	10ppm contour	50ppm contour	100ppm contour	190.66ppm contour
1	gas 1	no	strong	horizontal	7,072	1,920	980	500
2	gas 1	yes	strong	horizontal	1,864	640	310	150
3	gas 2	no	strong	horizontal	5,165	1,832	1,180	610
4	gas 2	yes	strong	horizontal	1,864	700	425	220
5	gas 1	no	weak	horizontal	15,640	2,200	1,020	500
6	gas 1	yes	weak	horizontal	4,520	680	285	125
7	gas 2	no	weak	horizontal	86,771	5,999	2,579	1,059
8	gas 2	yes	weak	horizontal	28,007	2,560	710	185
9	gas 1	no	strong	vertical	2,002	277	113	53
10	gas 1	yes	strong	vertical	551	92	39	18
11	gas 2	no	strong	vertical	3,619	295	113	51
12	gas 2	yes	strong	vertical	802	173	74	35
13	gas 1	no	weak	vertical	-	-	111	44
14	gas 1	yes	weak	vertical	1,223	88	31	15
15	gas 2	no	weak	vertical	25,926	458	108	42
16	gas 2	yes	weak	vertical	-	-	-	-

Table 1: Release Scenarios

Gas 1 = gas from condensate

Gas 2 = gas from oil

Gas Cloud Dimensions

The gas cloud in question is a cloud containing H₂S gas which has been released as a result of a loss of well control. The plume is described as the shape and size of the gas cloud and is considered to be a simple entity. For the purposes of the modelling the plume size and shape is calculated within the FRED software^[9] and this information is input to the Shell SHEPHERD software^[10] for use in the risk integration calculations. The plume calculations are simple physical calculations only as the complex behaviour of such a cloud in the actual environment cannot be closely modelled (e.g. to account for topography) using these software models.

Location Specific Individual Risk

The QRA involved identifying a range of potential major accident hazard scenarios associated with the planned drilling operations. The risk associated with the drilling operations is described numerically as the Location Specific Individual Risk (LSIR). LSIR is associated with a hypothetical individual who is positioned at a location for 24 hours a day, 365 days per year. It is calculated by considering the frequency of an event multiplied by the probability of the location being affected by each individual event, multiplied by a probability of fatality. LSIR is most commonly presented in the form of iso-risk contours. Figure 3 shows the risk results from the SHEPHERD modelling from all scenarios identified in Table 1.

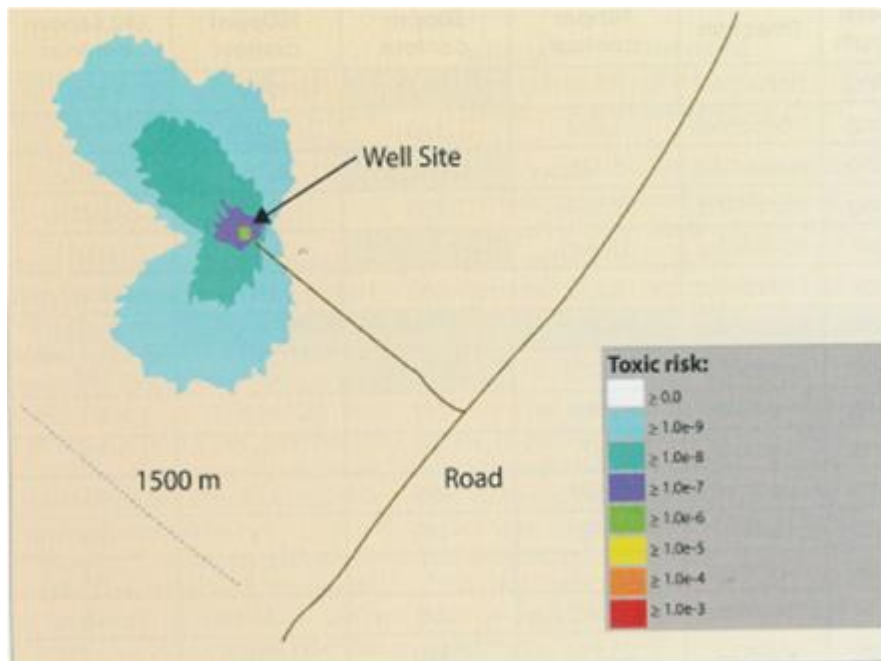


Figure 3: Risk Contours^[8]

It can be seen from Figure 3 that the maximum distance to the 1.00E-06 toxic risk contour is only 28m from the well, which demonstrates that whilst the potential consequences are long-reaching, the risk associated with the drilling operations is localised to the wellsite.

Bow-Tie Analysis and Risk Reduction

Whilst the QRA demonstrates that the risk at the settlement is tolerable, it does not alone, demonstrate that the risk is tolerable and ALARP. Therefore, in order to demonstrate that the risks were being managed to tolerable and ALARP levels a Bow-Tie analysis was performed. This identified the causes and consequences of a release which are shown in Figure 4.

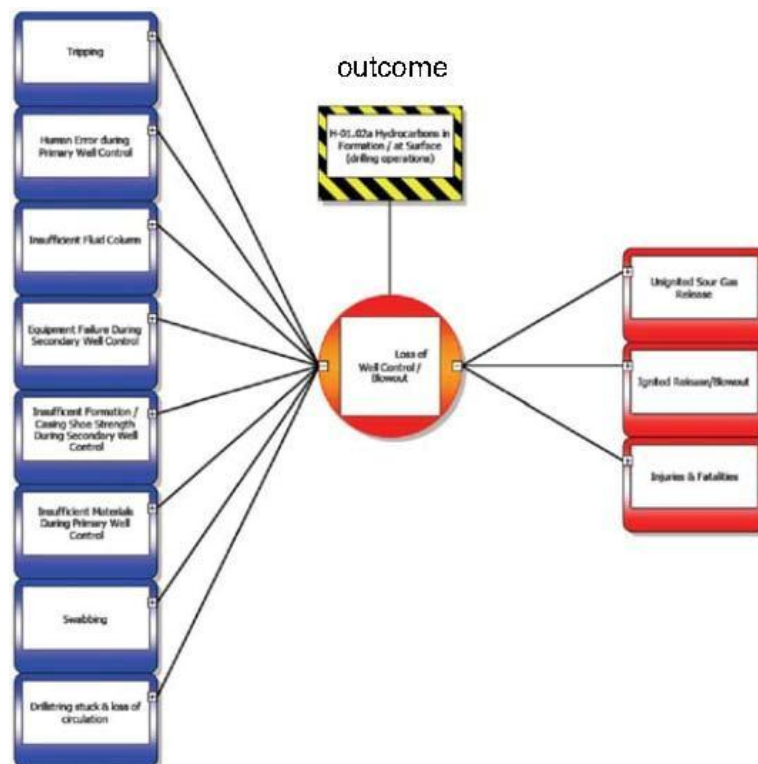


Figure 4: Well Control/Blowout Bow-Tie

The barriers to prevent a release were also identified as well as the threats which could lead to the consequences being realised.

The Bow-Tie analysis identified twelve risk reduction measures of which 10 were recommended for immediate implementation and two were recommended for further study. The risk reduction measures were categorized as:

- Equipment;
- Personnel;
- Procedures.

Risk Reduction Measures - Equipment

Most of the issues raised referred to specific issues with the existing configuration including alterations to the rig infrastructure and additions to associated equipment. The most immediate issue required a visit to the rig site to ensure that the side outlet valve was to be directed away from the settlement, which necessitated the site layout, to be re-orientated. The choke manifold also had to be adapted so that it could be changed out in the event of failure during circulation. A circulating device was installed to allow circulation and pressure control whilst running in the drill string. Radio communications equipment was vetted and updated to allow full communication in the event of an emergency.

Risk Reduction Measures - Personnel

Personnel measures centred on the use of a second drilling supervisor while breaking into the reservoir. This was considered essential to ensure that a senior member of staff was on site 24 hours a day who had full responsibility for emergency situations.

Risk Reduction Measures - Procedures

Procedures comprised two types with the most important being the company Emergency Response Plan (ERP). This was tested to ensure its effectiveness in answering an emergency from the rig site. Prior to the exercise personnel had their actions and responsibilities reiterated and were informed that the forthcoming exercise would test their effectiveness and readiness. The exercise was monitored by both company staff and external observers and the outcome was considered more than sufficient for requirements once a couple of points were clarified and their results passed back to the rig crew. Other procedures included ensuring all senior drilling staff and Toolpushers took an on-scene commander course along with other identified training. All operational procedures as per the Manual of Permitted Operations (MOPO) were to be revisited for all crew and reiterated in light of the requirements.

Well control training was also recommended and took the form of simulator training at the rig, under the guidance of a well simulator expert. All crew were taken through a scenario which involved an influx into the well to simulate the penetration of a high-pressure reservoir. The actions of each crew member were observed and where necessary the correct procedure for dealing with the situation was stressed and the exercise repeated.

Risk register

A “risk register” was set up to capture all recommendations of the Bow-tie analysis and to ensure that the necessary actions were assigned to responsible staff with clearly defined goals and schedules. This ensured that all of the identified actions and procedures were in place and understood.

Actions within the risk register were maintained by the “well owner” and available for all parties to continuously monitor towards successful completion of the well operation.

Results

The following results were derived from the assessment:

1. At 190.66 ppm (lethal concentration threshold) no releases are predicted to reach the road (1500m) or the settlement (5,000 m).
2. At 100 ppm gas 2, through open hole (no drill pipe), weak breeze scenario is predicted to reach the road, while no releases are expected to reach the settlement.
3. At 50 ppm, five of the horizontal releases but none of the vertical releases were predicted to reach the road. Only one release reaches the settlement – scenario 7 (gas 2, without drill pipe and with a weak breeze).
4. Maximum H₂S concentration at the settlement is approximately 60 ppm.
5. A 10 ppm plume width at the settlement is predicted to be between 240 m and 2,304 m (scenario dependant).
6. For an ignited well release (planned or unplanned), assuming all H₂S converts to SO₂, the 100 ppm contour for SO₂ is at 2,537 m from the well and the 394 ppm contour (UK HSE 1% fatality)^[12] at 340 m. The conclusion is that SO₂ does not represent a risk at the settlement.
7. A blow-out bow-tie was developed which identified twelve remedial actions for the well; ten of these were assessed

by the Project Team as being required to be implemented immediately in order to reduce the risk to tolerable and ALARP levels.

8. Risk levels are demonstrated to be tolerable and significantly below UK HSE risk tolerability criteria (at the settlement and the road).
9. Distance to 1.00E-06 per year LSIR contour (UK HSE risk criterion for public)^[13] is 28m from the wellsite for all possible events.

Conclusions

Based on the results of the analysis presented in this paper and the risk reduction measures recommended as a result of this analysis, the risk associated with the exploration well was considered tolerable and ALARP. The goal of the analysis was to review the possible scenarios and determine their risk level and recommend mitigation actions.

Only the worst case scenario resulted in elevated H₂S concentrations at the settlement. However, this scenario involves a horizontal blow-out with no drill pipe in the hole, a situation that is considered highly unlikely due to existing operational procedures; it is very unusual for any rig operation to be performed which involves pulling out of hole without bottom hole conditions being fully stabilized first. This significantly reduces the probability of this scenario occurring, further reducing the risk.

The well was subsequently drilled successfully without incident, and the approach described in this paper implemented as the framework for future high-sour exploration drilling operations in the organisation.

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Abbreviations

ALARP - As Low As Reasonably Practicable

ERP -Emergency Response Plan

FRED -consequences and modelling software

H₂S -Hydrogen Sulphide

LSIR - Location Specific Individual Risk

MOPO - Manual of Permitted Operations

QRA -Quantified Risk Assessment

SHEPHERD -Assessment of physical effects software

SO₂ -Sulphur Dioxide

UK HSE – UK Health & Safety Executive