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Semi-Quantitative HAZOP Methodology Applied to Upstream Oil & Gas Activities

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Recent off-shore drilling accidents showed that the consequence magnitude can be really disastrous; this suggest that a greater effort should be exerted to reach an advanced control of risks. In this framework this paper will show the advantages of a semi-quantitative HAZOP analysis applied to Upstream Oil & Gas operations. The paper will:

- Introduce and describe the use of semi-quantitative HAZOP analysis
  - Definition of likelihood and magnitude of consequences classes
  - Structure and characteristics of risk matrix
  - Definition of tolerability criteria; common and most used tolerability criteria
  - Use of risk matrix during HAZOP sessions to assess the tolerability of risk
- Apply the methodology to some examples to show how it allows more objective and consistent assessment, better evaluation of risk, protective measures and barriers
  - Example #1: off-shore oil reservoir drilling activities
  - Example #2: natural gas reservoir storage plants.

The classic HAZOP technique relies on the experience, knowledge and judgment of team members to asses if the barriers available to protect from a given scenario can be considered enough; likelihood and consequence modelling are developed only later, outside the team.

The semi-quantitative HAZOP introduces in the standard methodology the use of a risk matrix and a tolerability criterion.

Likelihood classes and consequences classes will be defined, and they will be the x and y axis of the matrix. The likelihood of events can be easily evaluated since in the Oil and Gas sector a large set of statistical, highly reliable, well organized data is available (OREDA, OGP, E&P forum, etc.).

The magnitude of consequences can be estimated using shortcut methods, or complete, detailed, complex consequence modelling (CFD, computational fluid dynamics models), considering damages to people, the environment, the plant, company reputation, and so on.

The tolerability criterion will be represented in the risk matrix dividing it in different areas, i.e. low risk (low frequency, low magnitude), unacceptable risk (high frequency, high magnitude), ALARP area.

For each deviation, after indentifying a scenario, the likelihood and the magnitude of consequences classes are evaluated. It's then possible to enter the risk matrix, verify the tolerability of risk, and find out if more barriers are needed.

This preliminary quantification of the risk will take place involving all the team members, hence leading to more consistent and shared technical choices.

The methodology will be applied to offshore drilling activities.

1. Scope of work

The suggested methodology applies to the upstream Oil&Gas industry. Also called exploration and production (E&P), used to refer to the searching for and the recovery and production of crude oil and natural gas. The upstream sector includes the searching for potential underground or underwater oil and gas fields, drilling of exploratory wells, and subsequently operating the wells that recover and bring the crude oil and/or raw natural gas to the surface.

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2. Risk matrix and risk tolerability

Sometimes, when reviewing a risk assessment, you can find situation where the concept of risk is identified with only one of the two of its components: likelihood of the event, or magnitude of consequences. As the definition of risk is the combination of the two elements (likelihood and magnitude of consequences) this approach is incomplete by definition, and can lead to misunderstandings. A remarkable example took place during the authorization process of a site under Seveso Directive: it was required to evaluate some events with a likelihood of $1*10^{-10}$ events/y, and to find protective measure to mitigate their consequences. If we consider that we could give to the “Big Bang” a likelihood of about $1{,}3*10^{-10}$ events/y, you can understand how such a request can be considered a nonsense.
From the opposite point of view, it makes no sense to consider negligible an event only by means of its likelihood: if we analyze an event with a likelihood of $1*10^{-6}$ (which means once every millions of years, and looks very unlikely) that could affect a large number of people (let’s say one thousand, the number is not overestimated; remember that the accident of Union Carbide in Bhopal caused more than 25 thousands fatalities), becomes evident that to assess the tolerability of risk we need a more complex (integrated) approach, referring to the definition of risk.
This goal is met using a quantitative risk assessment (usually called QRA), that evaluates: likelihood of events, magnitude of consequences, number or entity of targets affected and compares this set of information with a risk tolerability criteria, that can be described through a risk matrix.

A risk matrix is a matrix on which axes likelihood classes and consequences classes are set. A way to define likelihood classes is to divide by orders of magnitude, i.e. powers of 10 (Table 1). Different consequence classes can be defined according to the typology of effects: consequences on people, environmental damage, economical impact, reputation, etc. (Table 2). From these definitions derives the structure of the risk matrix, reported in (Table 3). The Matrix has been divided in three areas, corresponding to different levels of risk: Unacceptable risk, identified by the number “3”, ALARP Approach area, identified by the number “2”, and tolerable risk, indentified with number “1” (Table 4). For the definition of the ALARP approach you can refer to the UK approach (R2P2 report, see references). These are the instruments that will be used during a semi quantitative HAZOP session.

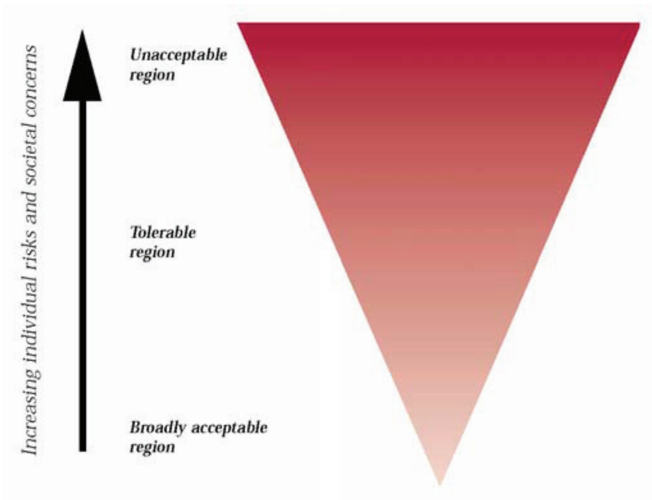

Figure 1: Tolerability of risk

3. Semi quantitative HAZOP

The semi quantitative HAZOP is based on the same principles as a classic HAZOP. The organization of the sessions, the composition of the team, the procedure are the same. The difference is that the frequency of causes, the reliability of protection and barriers, as well as the magnitude of consequences are numerically evaluated.
The process is developed for two situations (at least): potential (or raw) risk, that is without any barrier, and mitigated (or residual) risk, that is taking into account the available barriers; furthermore is possible to evaluate the efficiency of additional barriers by means of risk reduction. The evaluation of the potential risk

is very important, as it allows to know what would be the worst case scenario if all the barriers fail. Hence, it is possible to:

- • Enter data input for potential risk into the risk matrix, and evaluate the potential risk
- • Enter data input for mitigated risk into the risk matrix, and evaluate the tolerability of mitigated risk.

If the risk level achieved with the available barriers is not satisfactory, other barriers can be considered and their effect evaluated using the same procedure.

Table 5 shows the structure of a form that can be used in a semi quantitative HAZOP. The definitions used in the form, and the relevant values are described in Table 6.

3.1 Likelihood of events

Some highly reliable sets of data are available for the Oil and Gas industry to evaluate the likelihood of events (OREDA 2009, E&P Forum 1996, OGP 434, 2010). These sources provide: frequency for main deviation causes, reliability or probability of failure on demand of barriers. In Table 7 some examples of the available data are reported.

The likelihood is first assessed for the initiating event (i.e. the likelihood to have negative consequences from the deviation) without taking into account the available barriers, to allow the evaluation of potential risk. Then the available barriers are considered, together with their reliability in terms of probability of failure on demand (PFD). The likelihood of the initiating event can be multiplied by the PFDs of the independent barriers, to calculate the likelihood of the mitigated risk.

Referring to the example in table 5:

- • The likelihood of the initiating event (operational error in preparation of mud) is 10*10-1 event per year of continuous operations; this is the likelihood of the potential event
- • The specific and accurate training and procedures on mud preparation are considered a barrier reducing the likelihood of the scenario by an order of magnitude
- • The high mud level alarm (PFD = 10-1), together with the operational intervention activating the annular preventer (PFD = 10-1), reduce the likelihood by two orders of magnitude.

The likelihood of the scenario can be assessed in $10*10^{-4}$ events/year. The effect of further barriers on the risk level can be assessed considering their PFD: in the example pipe rams with PFD = 8,73*10-2 are considered.

3.2 Magnitude of consequences

Although many physical models and modelling software are available, during the HAZOP session there is no time to develop a complete numerical consequence modelling. Simplified models can be used; this allows to have an idea on the maximum distances reached by the negative effects of the events that will be analyzed during the HAZOP study:

- • Assume standard distances, i.e. maximum damage area (corresponding to 3kW/m2 heat radiation flux) for a pool fire is about 4 times the diameter of the pool
- • Use simplified models, such as EPA ALOHA to develop very fast calculations
- • Prepare, before the HAZOP session, some tables with referring scenarios; for example, if H2S is present in the plant, the damage areas for 0,1 kg/s, 1 kg/s, 10 kg/2 can be developed, and used during the sessions.

These solutions allow to have a rough, but precautionary, idea of the maximum extent of damage areas. Furthermore the environment surrounding the plant should be known, so that it is possible to have an idea of the presence of vulnerable targets, in means of safety for people, environment, etc. and verify if the damage areas can reach these targets.

With these information is possible to define the class of magnitude of consequences. If some critical scenarios are highlighted, it is possible to develop later more accurate calculations and review the related item.

3.3 Risk assessment using the Matrix

With the information collected according to the methodology described in the former paragraph, it is possible to enter the risk matrix and to set the risk level, according to the definitions in paragraph 2, and to verify if the risk is tolerable, or if further barriers are needed.

4. Case study - Offshore drilling operation

The case considers drilling operations on offshore platform. The most feared event for drilling operations is the blow-out, i.e. an uncontrolled escape of oil or gas from a well.

During drilling, the pressure of the reservoir fluid is counteracted by the hydrostatic pressure of the mud that is pumped through the drilling pipe, fills the well, and circulates back to the mud tank. As the level of the mud is equal to the depth of the well, the only controlled parameter is the density of the mud. Hence the mud density must be changed to have the hydrostatic pressure matching exactly with the pressure of the fluids in the reservoir. If the density of the mud is to high, the mud will flow into the reservoir and the fluid, which is lighter, will take its place in the well, coming to the surface; if the density is too low, the pressure of the reservoir fluid will push the mud out from the well top; these situations are defined as “kick”. If the kick remains uncontrolled, in both cases the fluid will come to the top of the well and will erupt in a blowout.

A blowout is a very dangerous event, as it involves very high flow of multiphase hydrocarbons, and in the worst cases also toxic substances as hydrogen sulphide (H_2S). The total flow rate can overcome 100 kg/s of hydrocarbons released. According to definitions in Table 2, the event can be easily classified as catastrophic, that is magnitude class 5. The first signal that something is going wrong is that the level of the mud tank will vary, according to the situation: is the mud density is too low, the mud level in the tank will increased, as the mud is pushed back to the surface; if the mud density is to high the mud level in the tank will decrease, as the mud get lost into the well. The other signal comes from the fact that some of the mud will be mixed with the reservoir fluid, and the light hydrocarbon components will flash as the pressure will decrease. So the control of the mud level and of the composition of the vapour flashing from the mud is critical to have an early detection of the kick and to assure adequate measures. When a kick take places, and is detected, the possible action is to close the top of the well using the blow-out preventers (BOP). The BOP are equipment designed to close the gap between the piping (drilling pipes) and the casing (the walls of the well). There are two main groups of BOP: annular preventer (an annular bag that is inflated and closes the gap between the piping and the casing), and rams, that are plates that are pushed against the piping. There are to types of rams: pipe rams, that are shaped to fit exactly the piping, and shear (or blind) rams, that cut the piping and close completely the well hole; blind rams are the last and extreme barrier.

After closing the well hole (with annular preventer) it is possible to prepare a mud with adequate density, circulate the proper mud into the well, using a dedicated circuit, until the equilibrium between pressure is reached; it is then possible to restart the normal operation. The success depends on the proper execution of all the operations and on the reliability of the instrumentation and BOP. The former description is put into HAZOP form in Table 5.

The frequency of the kick is assumed equal to operational error preparing a mud with wrong density ($5*10^{-2}$ event/year, likelihood class 5). Applying the risk matrix we obtain that the raw risk is unacceptable. The kick is identified by the high (or low, according to the case) level alarm on mud tank level. Revealed the kick, the operator must close the well, operating the annular preventer. The effectiveness of this phase, using data from literature, can be assessed with a probability of failure of 10^{-3}.

The risk level, considering the described barriers is in the ALARP zone, hence further measure are considered. The presence of the pipe rams, with a PFD = $8,73*10^{-2}$, allows the reduction of the risk to the lower limit of the ALARP Zone. If blind rams, with PFD = $1,5*10^{-2}$, are installed, the risk scores 1, and is tolerable.

Table 1: Likelihood classes example

Score	Definition	Likelihood [events/y]	Description
8	Very frequent	1	May happen at least once a year
7	Frequent	10^{-1} to 1	May happen several times over 10 years of life cycle of an installation
6	Occasional	10^{-2} to 10^{-1}	May happen one time over the life cycle of an installation
5	Possible	10^{-3} to 10^{-2}	may happen one over 20 to 30 years of life cycle and this for 10 to 20 similar installations
4	Rare	10^{-4} to 10^{-3}	May happen once every year for 1,000 similar units or an event that may occur once over 20 to 30 years of life cycle and this for 100 to 200 similar installations
3	Extremely rare	10^{-5} to 10^{-4}	Has already happened in the industry but that was subject to corrective measures
2	Unlikely	10^{-6} to 10^{-5}	A scenario that is physically imaginable but that has never happened
1	Extremely rare	Below 10^{-6}	

Table 2: Magnitude classes example

Severity	Consequence on people	Consequences on the environment	Economical impact
1 Moderate	Internal: medical treatment. External: no significant effects	Single permit overcoming, minor onsite environmental damage/contamination (<€80k cleanup cost)	<€250k
2 Serious	Internal: major injury External: reversible effects	Federal/state reportable quantity release, multiple permit overcoming, significant on-site environmental damage/contamination (€80k to €300k cleanup cost)	€250k -€2,5M
3 Extensive	Internal: multiple major injuries – fatality External: irreversible effects, public shelter in place	Major on-site environmental damage/contamination (>€300k cleanup cost), limited off-site environmental damage/contamination (<24 hr response)	€2,5M -€10M
4 Very extensive	Internal: multiple fatalities External: irreversible effects, fatality, public evacuation	Significant off-site environmental damage/contamination. short term impact (1 day – 7 day response), limited fish kill/river impact/ground water contamination	€10M -€100M
5 Catastrophic	Internal: many fatalities External: multiple fatalities	Major off-site environmental damage/contamination, long term impact (>7 day response), significant fish kill/river impact/drinking water supply impact	> €100M

Table 3: Risk matrix example

LIKELIHOOD							
	8	Very frequent, 1	3	3	3	3	3
	7	Frequent, 10^{-1} to 1	2	3	3	3	3
	6	Occasional, 10-2 to 10^{-1}	2	2	3	3	3
	5	Possible, 10^{-3} to 10^{-2}	1	2	2	3	3
	4	Rare, 10^{-4} to 10^{-3}	1	1	2	2	3
	3	Extremely rare, 10^{-5} to 10^{-4}	1	1	1	2	2
	2	Unlikely, 10^{-6} to 10^{-5}	1	1	1	1	2
	1	Very unlikely, < 10^{-6}	1	1	1	1	1
			1 Moderate	2 Serious	3 Extensive	4 Very extensive	5 Catastrophic
			SEVERITY				

Table 4: Matrix risk level definitions

Score	Definition	Description
1	Tolerable risk	The scenarios resulting in a risk level 1 with a moderate or serious severity should be reviewed as part of the workplace risk assessment
2	ALARP approach	Scenarios resulting in a risk level 2 require an ALARP approach ("As Low As Reasonably Practicable"): it must be demonstrated that it is not possible to reduce the risk level to an economically and socially acceptable cost.
3	Unacceptable risk	The risk cannot be accepted under any conditions; prevention or mitigation measure are needed

Table 5: Example of semi quantitative HAZOP form

Node	Deviation	Cause	Consequence	Potential risk			Existing Safeguards and PFD	Mitigated Risk			Additional safeguard	Reduced Risk		
				Lp	Cp	Rp		Lm	Cm	Rm		Lr	Cr	Rr
Drilling in reservoir	More mud level (kick)	Operational error in mud density preparation ($5*10^{-2}$)	High mud level in mud tank; kick; blow-out	6	5	3	Specific training on mud preparation (10^{-1}); High mud level alarm and Annular BOP(10^{-2})	3	5	2	Pipe rams ($8{,}73*10^{-2}$)	2	5	2

Table 6: Definitions and values of example in Table 5

Risk	Abbreviation	Definition	Value	Class
Potential risk	Lp	Likelihood	Operational error: $5*10^{-2}$ event/y	6
	Cp	Consequence magnitude	Blow-out: catastrophic	5
	Rp	Risk class	Unacceptable risk	3
Mitigated risk	Lm	Likelihood	Frequency of event considering the existing barrier: Specific training: 10^{-1} Annular BOP: 10^{-2} ($5*10^{-2}$ event/y * 10^{-1} * 10^{-2}= $5*10^{-5}$ event/y)	3
	Cm	Consequence magnitude	Blow-out: catastrophic	5
	Rm	Risk class	ALARP approach	2
Risk with additional barriers	Lr	Likelihood	Frequency of event considering the additional barriers : Pipe + blind rams: $8,73*10^{-2}$ ($5*10^{-5}$ event/y * $8,73*10^{-2}$ = $4,35*10^{-6}$ event/y)	2
	Cr	Consequence magnitude	Blow-out: catastrophic	5
	Rr	Risk class	ALARP approach	2

Table 7: Examples of reliability data from E&P forum

Initiating event	Failure rate [event/year]	Source
Leakage from flange, < 2", small leakage	$3,96*10^{-4}$	E&P forum, Process release and ignition
Leakage from flange, < 2", medium leakage	$1,31*10^{-4}$	
Processing piping, >2", small leakage	$1,14*10^{-5}$	
Processing piping, >2", medium leakage	$2,82*10^{-6}$	
Processing piping, >2", large leakage	$1,31*10^{-6}$	
Probability of ignition, worldwide, blowout	0,3 (probability)	
Probability of ignition, North Sea platform, small gas leak	0,005 (probability)	
Probability of ignition, North Sea platform, small oil leak	0,03 (probability)	
Probability of ignition, Gulf of Mexico platform, gas	0,8 (probability)	
Probability of ignition, Gulf of Mexico, oil	0,07 (probability)	
Probability of blow-out, US historical offshore, exploration	0,0061 (probability)	E&P forum, Blowouts
Probability of blow-out, US historical offshore, production	0,0023 (probability)	
BLOW OUT PREVENTERS (BOP)		
Annular BOP, leakage in closed positions	0,92	E&P form, Blowout prevention equipment
Pipe rams, fail to fully open	$8,7*10^{-2}$ (probability)	
Shear/blind rams, premature partially closure	$1,5*10^{-1}$	

5. Conclusion

The classic HAZOP Methodology (that is non-quantitative) shows its weakness when handling high level risks, particularly for the drilling operations. As it is shown in the example, the semi-quantitative HAZOP allows to:

- Estimate the risk level, by means of severity and likelihood
- Assess the tolerability of risk, using a risk matrix, where the tolerability criteria can be derived by international best practise
- Choose a correct number of barriers, according to the risk level, going beyond the experience of the HAZOP team, and achieving a high level of protection.

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