High Penetration Rates: Hazards and Well Control - A Case Study
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Abstract
Good agreement with field data has been obtained when using a commercial kick simulator to analyse a 56 bbl gas kick taken in a 59 deg deviated wellbore.

Fast kick detection and reaction are necessary when drilling at high rates of penetration since high pump rates, necessary for hole cleaning and cuttings transport, imply that a gas influx may be rapidly circulated to surface. A simulated example of a field kick is used to show how close to a blow-out it is possible to be with normal rig actions and response times; the tip of the gas cloud is less than 300 ft below surface and rising fast at shut-in. Benefits of earlier detection and shut-in are illustrated through simulation.

High penetration and pump rates result in dispersal of the influx along the annulus. This makes kick detection harder, since a greater proportion of the influx gas can dissolve in the drilling fluid. A simulated example emphasizes how influx detection can be significantly harder with an oil based mud than with a water based mud.

Gas migration results in a stabilised bottom-hole pressure much higher than the formation pore pressure. Subsequent use of standard field methods significantly overpredicts kill mud weight; alternative interpretation methods are suggested.

Based on the results of the simulations, procedural recommendations are made in order to minimize the risk of a kick and to enhance the probability of kick detection.

Circulation is dangerous if a potential influx could be pumped a significant distance up the annulus during the period of circulation. So, when making a connection, dangerous periods of circulation should only be carried out after completing the connection.

When the influx is dispersed along the annulus, surface pressures may take a long time to stabilise. Prompt use of the driller’s method in these cases gets the gas safely out of the wellbore and lessens possible misinterpretation of shut-in pressure rise.

Using simulation for well control contingency planning can help in early recognition of field hazards and in the confident choice of appropriate actions.

Introduction
Advanced well control simulators, (such as Anadrill’s SideKick simulator or Rogaland Research’s RF-KICK simulator), are currently being used for an increasingly wide range of applications, (e.g. well planning [15, 17, 26], contingency planning [18, 21, 26], post-event analysis [5, 28, 31], training and safety [2, 3, 6, 19], and are also being extended scientifically to model ever more realistic field scenarios, (e.g. [14, 16, 20, 23, 27, 31]), as well as addressing specific topics on a rig-site basis, (e.g., deep water well control [1, 22], mud-gas separator sizing [24]).

This short paper presents a case study in which a commercial well control simulator (SideKick) is used to simulate a field kick and the results are compared against actual measurements from the rig. The SideKick simulator has been validated against both experimental and field data sets, (see [29, 32] for an overview of its development). Recent
extensions of the simulator capabilities include the modelling of high wellbore deviations, slim-holes, multiple kick zones, multiple influx fluids, wellbore compliance, fluid loss, parasite string and gas injection, see [25].

Two main purposes are served by conducting post-event analyses such as this.
1. Model validation requires that simulated results and measured data compare favourably.
2. The simulator computes a physical description of the entire wellbore, which is obviously more informative than measurement of surface pressures, inflow mud weight and pump rate, (the driller's basic data during a kick). This additional information can be valuable in analysing rig activity a posteriori, thus making recommendations for safer future drilling practices.

Both aspects are addressed in this paper.

Events on the rig
From the extensive data available it is possible to put together an accurate picture of the sequence of events on the rig during both the kick/shut-in phase and the kill phase of the well-control operation, (see figure 1).

Kick and shut-in. This kick occurred whilst drilling a 59 deg deviated section of 12.25 in hole at a measured depth of 3314 ft (vertical depth 2474 ft), in shallow water, (see figure 2). After the incident, when the well was brought under control, the formation pore pressure was estimated at $\pm 1600$ psi.

The position of the kicking zone was found from caliper readings, which showed a large washed out zone (diameter $\pm 18$ in) at the bottom hole depths reached during drilling the last stage. The kick is assumed to have started when the bit first penetrated the depth of the washed out zone. For some time prior to the kick, average rates of penetration (ROP's) in the range 200-400 ft/hr were recorded. Just before the kick was drilled, peak ROP's were as high as 520 ft/hr. Drilling mud weight was 10.7 lb/gal and the pump rate was 940 gal/min.

Drilling stopped 8 minutes after first penetrating the overpressured zone. Circulation continued for 5 minutes so that a MWD survey could be made. It was only after circulation stopped to make a connection that the well was observed to be flowing. Pit gain measurements were obscured by additional flows into the main pit from two centrifuges left running at the shaker, as well as by backflow from the surface lines. At this point the drillpipe was in the slips and the top drive on the way back up the derrick. After picking up and making up the stand, the well was shut-in, 3.5 minutes after mud circulation had stopped and 16.5 minutes after the start of the kick. The total kick volume was estimated at 56 bbl. Initial shut-in pressures were 200 psi on the drillpipe and 480 psi on the casing. These stabilised at 745 psi and 943 psi, respectively, after about one hour.

Killing the well. From the final stabilised shut-in pressures, a kill mud weight of 16.8 lb/gal was calculated. Sufficient barite was available to weight up the combined well (456 bbl) and active pit (502 bbl) mud volumes to 15 lb/gal. A final circulating pressure was calculated for this mud weight and circulation commenced at 236 minutes, the aim being to get the gas out of the well while waiting for more barite to arrive at rigsite. An intermittent kill schedule was followed for the next 325 minutes. Periods of circulation were interspersed with periods when the well was shut-in and the active mud pit was again weighted to 15 lb/gal, (see figure 1b). Eventually, the remaining drillpipe pressure was bled off, the choke was opened and a flow check established that the well was dead.

Simulation results and validation
The above sequence of rig events has been broken down into a series of distinct control steps, suitable (see, e.g. [28]) for input into the kick simulator. Comparison of the simulator output with data measured on the rig provides validation for the underlying mathematical model in the simulator. This kick is particularly useful for validation purposes, since the well control operation is complex and lasts a total of 561 minutes. This makes it a challenging test for the simulator, (one might expect that simulation accuracy will decrease over a long time).

Surface pressures. A comparison of computed and measured drillpipe and casing pressures is shown in figure 3. There is a slight overprediction of the initial shut-in pressure rise rates. However, final shut-in pressures are approximately correct, as is the prediction of pressures during the kill. The pit gain computed in the simulation is 2 bbl less than the estimated actual value.

Gas migration modelling. Experimental and theoretical work carried out at Schlumberger Cambridge Research (SCR) has resulted in a comprehensive semi-empirical model which describes the gas slip behaviour, including the effects of wellbore deviation (up to 90 deg), annular geometry and local void fraction, see [11, 12, 13, 14, 29]. Interestingly, the experiments show that the peak gas slip velocities occur for deviations in the range 40-50 deg. In deviated wellbores the drillpipe will usually be eccentrically positioned, (on the low side). The gas then tends to concentrate near the top of the borehole, where the liquid velocity is greater. Drag on the bubbles is reduced. For very high deviations, buoyancy effects are reduced. See [12] for further explanation. This gas slip model is incorporated in SideKick, enabling prediction of the gas distribution within the annulus at all times during the simulation.
Gas distribution at shut-in. Figure 4 shows the simulated distribution of free gas void fraction within the annulus as the kick progresses. The blow-out preventers (BOP’s) were closed 16.5 minutes after drilling the kick, at which time the tip of the gas is only 270 ft from the surface. Continuing the simulation indicates that gas reaches the surface about 100 seconds later. Without closing the BOP’s at all, gas expansion massively accelerates the process: the last 100 ft of annulus are evacuated 17 minutes after drilling the kick.

Interpretation and Discussion
Three factors contribute to the proximity of the gas to the surface.

1. Circulation after the kick was drilled and before the well was observed to be flowing and shut-in.
2. Deep and fast penetration of an overpressured formation.
3. Gas migration, relative to the mud.

Mud circulation and displacement. The total volume pumped between drilling the kick and closing the BOP’s is 206 bbl (plus an additional 54 bbl of influx). Comparing this volume with the volume of the annulus shows that the effect of circulation and influx displacement alone would put the top of the gas cloud at 1132 ft below surface, (i.e. 2182 ft above bottom hole). This moves the gas towards the surface at £8040 ft/hr during the drilling and circulation phases.

The mud circulation rates are not excessively high, considering the hole size and ROP. Rigs of the type involved in this incident are capable of peak pump rates of about 1200 gal/min. A further simulation illustrates the possible consequences of this high circulation rate. Using otherwise identical model parameters as for the field kick simulation, but circulating at 1200 gal/min instead of 940 gal/min, dissolved gas is seen at surface 10.6 minutes after first penetrating the overpressured zone. Free gas follows a minute later, while the survey circulation is being carried out.

As well as immediately prior to shut-in, free gas void fraction distributions are plotted at both 10 and 13.5 minutes after drilling the kick, (figure 4). After 13.5 minutes, had the rig equipment been ready and the kick detected immediately after circulation stopped, the BOP’s could have been closed. The tip of the gas cloud was about 900ft below surface. Alternatively, if the MWD survey had not been carried out, the kick might have been detected and the well shut-in 10 minutes after the kick start time; the gas tip was 1400 ft below surface. Quick shut-in at either of these earlier times would also have resulted in a far smaller kick volume, (17.5 bbl for a 30 second shut-in after 10 minutes and 33.5 bbl for a 30 second shut-in after 13.5 minutes). This minimises risk; see also [10].

High Rates of Penetration. In this well control event, high ROP is believed to be the most significant potentially hazardous action. Two consequences of high ROP are:
1. In order to remove cuttings, pump rates will not be low. Thus, the effects of mud circulation discussed above, are in part due to the high ROP.
2. Drilling a kick at a high ROP exposes overpressured formation quicker, increasing the kick size.

To illustrate the positive effect of a low ROP, a simulation has been run using the same model parameters that were used for simulating the field kick, but drilling at half the ROP. This exposes only half as much of the overpressured formation, at half the speed. For this computed example, pit gain was only 18.3 bbl, (cf. 54 bbl). Also important, the tip of the gas cloud is more than 900 ft below surface at shut-in. Shut-in casing and drillpipe pressures rise to 743 psi and 675 psi, respectively.

In the field kick, the kick is drilled 6 minute after the start of the joint. A second simulation was run to examine what might have happened, had the formation been drilled with the same ROP at the start of the joint. The computed results suggest that about 10 bbl would have been taken by the time drilling stopped, (cf. 5bb). At this time, dissolved gas is seen at surface. Just a few minutes later 20 bbl of pit gain are registered and free gas is at surface. If the post-drilling circulation period had been carried out, a large section of the annulus would have been quickly evacuated.

Influx rate is approximately proportional to the height of exposed formation. To calculate kick volume, this must be integrated with respect to time. At constant ROP, this implies a quadratic increase in kick size with ROP. However, this is a non-conservative estimate. Gas in the annulus can increase the underbalance. Until shut-in, gas kicks are dynamically unstable self-accelerating events.

Gas migration, dissolution and dispersion in the annulus. Circulation and displacement places the gas cloud tip £1132 ft below surface. The remaining £862 ft difference (see figure 4) is due to gas migration. Thus, the mean gas migration speed during the period from drilling the kick until the BOP’s are closed can be estimated at £3120 ft/hr.

This migration rate is not particularly high. For significant gas volumes in drilling mud, (>10%), slip velocities £6000 ft/hr are quite typical, see [14]. With the water-based mud (WBM) which was used to drill this well, high mud circulation rates succeed in distributing the kick volume along the length of the well. The peak void fraction of free gas, when the mud circulation is stopped, is only 15% and for much of the annulus the void fraction is less than 5%, see figure 4. Depending on mud rheology, gas void fractions in the range 0-5% can be held in the mud in the form of small bubbles, (i.e. they do not migrate). This helps to explain the relatively slow migration of
the tip of the gas cloud, relative to the mud. See [14] for a more detailed discussion of the effects of gas suspension.

A phenomena which is not hazardous in this particular field kick, but is a potential hazard in similar situations, is gas dissolution. When using an oil-based mud (OBM), gas dissolution effects can be much more marked than with a WBM, (see e.g. [28]).

To illustrate gas dissolution hazards, the field kick simulation has been re-run using a 70% oil-based mud. Mud density, rheology and all other model parameters are kept the same and simulation timing is based on the original kick. The total mass of gas in the wellbore is shown in figure 5a, compared to that for the WBM. Note that the total mass of gas, when the well is fully shut-in, is approximately the same for both WBM and OBM. However, most of the gas is now dissolved in the OBM. The peak void fraction computed before circulation stops is only 8%. As the influx is circulated out of the well, at near surface pressures and temperatures the saturation solubility of the OBM will decrease and the influx gas will come rapidly out of solution. There will be approximately the same gas volume to handle at surface as for the WBM. A major difference between these two scenarios is that the total pit gain is only 14bbl in the case of the OBM, (figure 5b); most of the gas is hidden.

Pit gain is often the primary indicator of having drilled a kick. When does the crew react to the pit gain? Advanced kick detection systems (see e.g. [7, 8]), might give an indication at about 5 bbl. With normal rigsite information and equipment, 10 bbl is probably a more realistic figure to which the crew can react. In this case (figure 5a), a 10 bbl pit gain is registered about 5 minutes later for the OBM than for the WBM. Further simulations show that, for this length of delay to shut-in, the final mass of influx gas can be more than double that of the WBM. It is clearly important to distinguish here between the “kick size” used in detection and the “kick size” which must be circulated from the wellbore.

Note that it is the high circulation rates that allow such a large mass of gas in the wellbore. Without circulation the influx is not pumped up the annulus, but must displace mud. At the kicking zone the mud will quickly saturate and the influx gas will contribute directly to observable pit gain, which implies detection, which implies shut-in. Circulation disperses the influx along the wellbore, allowing it to dissolve and to become suspended in the mud. The same mass of influx is harder to detect, but is pumped nearer to surface. This situation should be avoided.

In figure 5a it is also noteworthy that the gas influx into the OBM takes so long to stop. This is a consequence of continual slow dissolution of free gas as it migrates. Gas dissolution counteracts the effects of gas migration, allowing a slow trickle of gas into the wellbore.

Finally, gas dissolution is not usually thought to be significant when using a WBM. However for the field kick, about 8% of the total mass of gas is dissolved in the WBM. This is only possible due to dissolved gas dispersion, caused by mud circulation.

Shut-in pressures and kill mud weight. The purpose of conventional well control procedures is to regain primary control of the well. This involves making an estimate of the formation pressure from the stabilised shut-in drillpipe pressure (SIDPP). During a shut-in period, gas migration will increase the wellbore pressure. When the wellbore pressure exceeds the formation pressure at the influx zone, the kick will stop. It is therefore, this downhole shut-off pressure which one wishes to estimate from stabilised surface pressures. Gas migration means that the bottom hole pressure when the surface pressures have stabilised is always more than the bottom hole pressure when the formation shuts off. Use of the stabilised pressures therefore results in a conservative estimate of formation pressure and consequently in an over-prediction of the mud weight necessary to kill the well.

Two potential dangers of over-prediction are:

1. Excessively heavy kill mud could induce fracturing.
2. Delayed circulation of kill mud, since there may not be enough barite at rigsite, (a typical minimum requirement in the field is to keep sufficient barite to weight the active mud system by 1 lb/gal).

Usually, the over-prediction of kill mud weight (KMW) is not severe. In this case however, formation pressure and KMW are over-predicted by 500-600 psi and ±4.3 lb/gal, respectively.

Billingham et al. [4] have analysed surface pressure rise during shut-in, by using a simplified wellbore model. They advocate the use of a curve fitting technique to determine the time when at which the shut-off pressure is reached. At this time shut-in pressure rise becomes linear, see [4]. This approach is practical for quick computations and can be programmed into rig data acquisition systems. Without automation, the same estimates can be made by eye from a graph of the shut-in drillpipe pressure, opening the way for human error. In cases such as this, where the sparse gas distribution prior to shut-in leads to relatively slow and steady surface pressure rises, the potential for human error is likely to be greater.

Kill Procedures. The procedure used to kill the well was effectively a hybrid between the wait and weight and driller’s methods. There was a long delay (±200 minutes) before kill mud circulation commenced, during which time the mud
weight was increased. Since a (nominally) underweight kill mud was used, the kill procedure also resembles the first circulation of a driller's method. The periods of shut-in during the kill are times when the active mud pit is weighted up.

Had a better estimate of the formation shut-off time been derived, the well might have been killed with the wait and weight method, using a mud weight of $\pm 12$ lb/gal. In this case, sufficient barite is likely to have been available at rigsite and the circulation might have commenced relatively soon. Alternatively, a straightforward driller's method kill procedure would have circulated the gas from the wellbore soon after shut-in, minimising the pressure rise. This would also have allowed time for better interpretation of shut-in pressures and for barite delivery.

The effects of using standard procedures, in either of the above scenarios, is indicated in figure 6. Circulation commences after 30 minutes of shut-in in both cases. Figure 6a shows the casing shoe pressure during the different kill procedures, figure 6b shows the mass of gas. Peak casing and surface pressures, total time before all gas leaves the wellbore and lost time on the rig are all reduced in either case. Nearly 6 hours of rig time might have been saved by performing a standard (textbook) well control procedure. Because there was insufficient barite on board to perform a standard wait and weight kill, (for the field estimate of KMW), the driller's method was the natural choice.

Conclusions
The results presented in figures 3 provide good evidence for the validity of the underlying physical models in the simulator. The most significant cause of the gas motion towards surface was circulation, as verified by simple volumetric arguments. Nevertheless, the effects of gas migration are also significant. Gas can slip fast in deviated wells, [14].

The eventual shut-in pressures computed are correct within 5%. Many factors, some poorly quantified, affect shut-in pressure rise rate, (e.g. fluid loss, wellbore compliance, mud compressibility, influx rates, gas solubility, gas slip; see [23]). Therefore, the error in predicting shut-in pressure rise rates does not indicate any major inadequacy of the simulation code. The total pit gain in the simulation is approximately correct; final shut-in pressures then depend mostly on having the right amount of gas, expanded to the right volume, at the right point in the wellbore. Given the complexity of the problem, the results are pleasing. Further validation of the simulator against field data is given in [28].

As the gas nears the surface, it expands and accelerates very quickly. Assuming that the simulator results are correct, the well was shut-in only just in time to prevent a serious incident. A number of important points have been highlighted:

- Drilling at high ROP’s, with consequently high mud circulation rates, requires increased awareness of the effects of taking a kick. In the case considered, when pumping at $\approx 900$ gal/min, the time taken for mud to reach the surface from bottom hole in the annulus is less than 18 minutes. This severely limits the allowable response time.

A second effect of high circulation rates on a kick is to distribute the influx along the wellbore. For mud systems where gas solubility is high, this could have the effect of significantly masking the size of kick taken.

- High ROP’s during kicks expose more formation. Since a gas kick is generally an accelerating phenomena, kick size can be significantly affected by ROP. In the example considered, halving the rate of penetration reduced the kick volume by a factor of 3.

- Pit volume increase is a primary indicator that a kick has been taken. Masking of pit gain by surface flows delays shut-in. The importance of “pit discipline” [15] can not be overemphasized.

- A quick hard shut-in minimises risk.

- Significant overprediction of kill mud weight can occur using standard field methods, especially in situations when shut-in pressures take a long time to stabilise. In this field kick, the well was shut-in for $\approx 200$ minutes before kill mud circulation began. The pressure rise lasted for $\approx 100$ minutes, which suggests that the stabilised SIDPP may not be a true indicator of the shut-off bottomhole pressure.

  - A more advanced interpretation of shut-in surface pressure rise would be one possible remedy. Standard methods may let you down in non-standard situations.

  - Another would be to slowly bleed off some of the shut-in pressure through the choke. If both SICP and SIDPP fall consistently when bleeding, this would confirm that the bottom hole pressure is above formation pressure.

  - Alternatively (and safer), if insufficient barite is available to kill the well and the shut-in pressure rise appears to be linear, consider the driller's method to get the gas out of the well early, whilst waiting for extra barite.

Most importantly, the practice of pumping mud after drilling a joint and before making a connection has been demonstrated to be potentially dangerous. There are numerous routine situations in which one might wish to circulate prior to making a connection, (e.g. MWD survey, cuttings removal). It is important to evaluate whenever such an action might be
dangerous.

- It is not hard to make simple volumetric calculations of the time taken to circulate bottoms up at different pump rates. Subtracting the time taken to drill the last joint gives the maximum possible time for which one should ever consider circulating. Since gas will expand and slip, this estimate is non-conservative; in reality there might be much less time available.

- Is the circulation period really necessary prior to connection? If the well was not flowing during or before connection, it is unlikely to flow with the additional circulating pressure after connection. If circulation is necessary before connection, can the circulation rate be reduced? Is it possible to flow check first? At the very least, be aware of the situation and be ready to shut in.

The use of advanced well control simulators for post-event analysis is clearly useful. However, use of simulation in well control (i.e. contingency) pre-planning is a far more powerful tool. In this incident, computation of SIDPP for a range of different kick sizes could have given the crew confidence to correctly predict bottom-hole pressure and circulation could have commenced sooner. Running a number of “what-if” simulations could also have helped the crew to evaluate the risk of their high rate of penetration and to balance this risk against the benefits.

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References


Figure 1: Rig operations before, during and after the kick
Mean Sea Level 157’

20” Conductor ; 474’TVD

13 3/8” Casing ; 1863’ TVD ; 2117’ MD

59 degree inclination from vertical

Kick Point ; 2473’ TVD ; 3314’ MD

Figure 2 : Wellbore schematic

Figure 4 : Distribution of the free gas in the annulus at various times after drilling the kick

Figure 3 : Comparison of field data and simulation results: a) drillpipe pressure, b) choke pressure
Figure 5: Comparison of simulation results for oil- and water-based muds: a) total mass of gas in the wellbore, b) pit gain.

Figure 6: Comparison of field data and simulation results for killing the kick; simulated driller’s and wait & weight methods: a) casing shoe pressure, b) mass of gas in the wellbore.