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Early Kick Detection Methods and Technologies

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Abstract

Early Kick Detection (EKD) is one of the most important areas for improvement in well control safety. The need for earlier, more accurate, more reliable kick detection across a wide range of drilling operations has become increasingly important as more operations are being conducted in deep water with increasingly tight pressure margins. In order to accomplish this, it is important to start measuring the indicators that have the greatest impact. This paper identifies and proposes two risk based Key Performance Indicators (KPIs) related to kicks: how long it takes to positively identify a kick, and how long it takes to respond to a kick once the identification is made. These KPIs are the Kick Detection Volume (KDV) and the Kick Response Time (KRT) respectively. They provide the ability to directly measure kick detection and management approaches. A third metric, the Drilling Mode Kick Frequency (DMKF), while not a performance indicator, is critical to help determine the point at which drilling operation kicks are most likely to occur and thereby to aid in the evaluation of kick detection methodologies. This paper discusses and compares technical approaches to early kick detection including how they relate to safety, efficiency, and reliability over a range of common deep water operations. By identifying “actionable” indications of a kick, a general approach is suggested to help focus on technologies leading to the most likely improvements for EKD. Irrespective of the EKD optimization path chosen however, the proposed KPIs can be used to quantitatively evaluate and compare the performance of different technologies and operational strategies.

Introduction: The Significance of Early Kick Detection

Early Kick Detection (EKD) is one of the most important focus areas for preventing Loss of Well Control (LWC) events in the Gulf of Mexico and elsewhere. The definition of Loss of Well Control as provided by the Bureau of Environmental Enforcement (BSEE) is[i]:

- Uncontrolled flow of formation or other fluids. The flow may be to an exposed formation (an underground blowout) or at the surface (a surface blowout).
- Flow through a diverter.
- Uncontrolled flow resulting from a failure of surface equipment or procedures.

EKD research and testing have been ongoing for the past decade although the importance of EKD has been amplified in the post-Macondo era. When kicks are accurately detected and recognized early they can be more readily managed and stress levels on equipment and personnel can be reduced, thereby lowering the risk of adverse consequences. Normal operations can resume safely and quickly. Two recent observations related to the importance of EKD are:

- An analysis of the Bureau of Safety and Environmental Enforcement’s (BSEE’s) incident database has shown that approximately 50% of drilling[ii] related LWC events could have been prevented or ameliorated with early kick detection.
- Not properly reading or interpreting kick indicators was a key factor in the Macondo accident.[iii] This suggests that an EKD system providing direct and unambiguous indications of a kick could have alerted the crew significantly

earlier. This may have helped the crew to avert the disaster that led to the loss of 11 lives and billions of dollars in environmental and economic damages.

Proposed Performance Indicators for Analyzing Kick Detection and Kick Management

For purposes of this paper, a kick is defined conventionally as an unintended flow of formation fluids into the wellbore. Kicks occur when the pressure in the well falls below the pore pressure of the formation. Not all kicks are serious events. However, as formation fluids displace heavier fluids in the wellbore and the pressure in the well drops further, the cycle can feed on itself and accelerate; and the kick can grow. When a kick is undetected or unmanaged, dangerous situations can happen in a matter of minutes. The appropriate response is to shut in the well as soon as possible.

The importance of detecting and responding to a kick quickly is widely recognized in the industry and many companies keep track of a variety of metrics concerning kicks (e.g. locations, frequencies, intensities, size of kicks taken, operations occurring when kicks are taken). In this paper we propose two Key Performance Indicators (KPIs) with regard to kick safety that require special consideration and consistent tracking:

1) Kick Detection Volume (KDV): How much of an influx occurs before it is positively identified as a kick?
2) Kick Response Time (KRT): Once a kick has been positively identified, how much time elapses before well control procedures have stopped the influx from progressing?

Kick management involves two parts: detection and response. The KDV is a measure of detection while the KRT measures the response. Both of these should be considered KPIs of safety, since they measure parameters that directly combine the technological capabilities and operational efficiency of the rig, as far as kicks are concerned. Currently none of these appear to be tracked consistently. The KDV is cast in terms of volume because it is the volume measurements that most often provide the positive indicator of a kick. Normally it is also the volume of a kick that is proportional to its risk; hence, volume is the parameter that ultimately needs to be minimized – even if the kick is detected through flow.

The KRT is uniquely a measure of operational performance since it is relatively insensitive to kick intensity; it takes roughly the same amount of time to stop a low intensity kick as it does a high intensity kick using a given set of well control procedures. The KRT can of course be readily converted to a volume when it is multiplied by the rate of influx, although the main value of this metric is expressed as a *time*. As the focus of this paper is on EKD, the management implications of this metric are being developed in a future paper (currently in preparation).

In addition to these two KPIs, we also propose a third metric:

3) Drilling Mode Kick Frequency (DMKF): What is the relative frequency of kicks for each drilling mode?

DMKF is a metric that sorts kick frequency by drilling mode, since the causes of kicks and the practical methodologies for kick detection are far from uniform. This metric is not a KPI, although capturing it on a company or even industry wide basis is critical for evaluating kick detection and response methodologies. EKD systems for example do not always work for all operational modes. Each type of operation needs to be examined independently. Historical databases record some of this data, although a more systematic approach is urgently needed.

We have identified five main drilling related operations that are estimated[iv] to comprise roughly 95% of all drilling kick events in the Gulf of Mexico. From an EKD perspective, it would be extremely helpful for the industry to systematically collect this data, and then use the results to inform both kick detection and management procedures. We recommend that the industry include and utilize the KDV and the KRT as well as the DMKF as part of their kick databases. The instrumentation on nearly all current rigs is suitable to allow capturing this information.

Of course these metrics are not exhaustive. One should also include the total number of bbls that were taken during the time it took to shut in the well (e.g. KRT), the shut-in well bore pressure; shut-in drillpipe pressure, kick tolerances, and the mud weight. In part, these will enable one to calculate the inflow rate and kick intensity, but as Key Performance Indicators, the KDV and the KRT are in a class by themselves -- they measure the cumulative effects of technology and operational procedures and crew performance. Whether new EKD technology is introduced or operational policies are changed, the net impact relative to kick detection can be ascertained by these two performance indicators. Additionally, while this paper is focused on the Gulf of Mexico, the reach of these KPIs is considerably greater as their utilization can be applied in other parts of the world as well in land based drilling.

The Early Kick Detection Operation Comparison Table

The EKD comparison table below (using two of the three metrics defined above) effectively illustrates the main precept of this paper that flow metering represents the next major advancement for EKD in the Gulf of Mexico. Unfortunately, kick data from which one can extract the above metrics is not widely available for analysis. Thus we have made some educated guesses for these parameters that have been used for the table below. The remainder of this paper is a discussion leading to the results summarized in **Table 1**.

Table 1— Early Kick Detection Operation Comparison Table

		Tripping Out	Making a Connection	Drilling Ahead	Out-of-the-hole	Plug & Abandon
Estimated Drilling Mode Kick Frequency (DMKF) (%)		15%	70%	5%	<5%	<5%
Conventional Drilling Base Case	**Primary Kick Indicator(s)**	Trip Tank	PVT (w/FP*)	PVT	Visual	PVT
			Flow Indicator	Flow Indicator	Trip Tank	Flow Indicator
	Backup Indicator(s)	PVT (stand average)		PWD	PVT	Stand Pipe or Cement Unit Pressure and Barrel Counter
				Stand Pipe Pressure		
	Estimated Kick Detection Volume (KDV)	~3 bbl	>10 bbl	>10 bbl	~5 bbl	>10 bbl
Conventional Drilling Using an Outflow Meter	**Primary Kick Indicator(s)**	Trip Tank	Flow Meter (w/FP*) and Boost Pump Strokes	Flow Meter & Pump Strokes	Visual	Flowmeter & Pump Strokes
		Flow Meter**	Flow Indicator		Flowmeter	
	Backup indicator(s)	PVT (confirmation and backup)	PVT (confirmation and backup)	PVT (confirmation and backup)	PVT (backup only)	PVT (confirmation and backup)
				PWD Stand Pipe Pressure		Stand Pipe or Cement Unit Pressure and Barrel Counter
	Estimated Kick Detection Volume (KDV)	~1 bbl	~5 bbl	~3 bbl	~5 bbl	~5 bbl

*FP stands for Finger Printing

**If the Flow Meter is located upstream of trip tank

Kick Indicators and Early Kick Detection

Conventional Drilling textbook kick detection indications are as follows:

1) Flow rate change (deviation from an established pattern);
2) Increase or gain in pit volume;
3) Flow with pumps off (any flow from the well when not pumping).

Primary Kick Indicators. The first of the three conventional kick indications relies primarily on a relative flow indicator. The second uses either the Pit Volume Totalizer (PVT) or the trip tank volume indicator. Flow sensors and volume indicators include:

- *Flow-out sensors* are primarily qualitative and in practice are not usually "actionable" by themselves – meaning that it requires additional indicator support before a driller has positively identified a kick and will take action to control it.
- *PVT* volume measurement systems are typically instrumented and use sonar or other sensing techniques to determine the level of the fluid in the tanks. In some cases multiple sensors are used and averaged to help reduce noise. Even with this instrumentation however, the sensors are inherently limited by the relatively large size of the tanks themselves, often with surface areas measuring 400sq ft or more. In this example, a borderline detectable fluid level rise of 1" translates into roughly 6 bbls, which may be masked to some degree on rigs experiencing significant wave heave. The reliable detection limit is estimated to be on the order of 10 bbls. When an increase of this size has been detected by the PVT, this can be a stand alone, actionable indicator. Quite often however a flow check is conducted to confirm that the pit increase is actually caused by flow from the well.
- *Trip tanks* are much smaller than the main mud pits, typically 20-50 bbls and are designed specifically for accurate readings. Trip tanks can detect changes of a fraction (~¼) of a barrel, and are commonly the most accurate influx (or loss) volume detectors on the rig. The trip tank is an actionable indicator but can only be used when the well is not being circulated.

Volume changes are usually alarmed although alarm settings are often made at the discretion of individual drill crews. Alarm settings are very important since multiple false alarms can establish tendencies to ignore the alarm altogether, even when it is real. Improper alarm settings will ultimately increase the KDV performance indicator.

Secondary Kick Indicators. Secondary kick indicators consist of a variety of measured, observed, and calculated results that warn that a kick may be imminent. Examples of measured results are pressures and temperatures (both downhole from PWD and at surface on the rig). Some examples of observed results are: mud property changes; cutting size changes; increase in background and trip gas. There are also calculated results such as the “d exponent.” All of these help to warn of a possible impending kick.

Secondary indicators are generally non-actionable by themselves. Nevertheless they are highly significant because they are often the first warning signs that a driller sees indicating that the drill bit is entering a zone where a kick may occur. Additionally they can be combined with primary indicators to dictate or trigger certain operational procedures that can greatly improve kick detection. For example, as soon as one or more of the secondary indicators indicate that one is entering a zone where kicks could occur, it may make sense to shut in the well at the first sign of a flow rate increase whether or not it is coupled with a volume increase from the PVT system. Drilling policies are often set based on knowledge of the formation and the location of the well. These policies will directly impact the KDV.

Here we make some important observations regarding secondary parameters:

1) The normal time when “measured” secondary parameters are available is when the drill string (where the sensors are located) is at the bottom of the hole. Yet kick frequencies for this operation are estimated to account for only a fraction of the percentage of total kicks suggesting that a broader approach should be considered first.

2) Secondary indicator parameters (e.g. pressure, temperature, d-exponent), when they are used are generally quite functional. Improving the measurement accuracy of these parameters however is *not* expected to be a path toward improved kick detection.

For these reasons we suggest that focusing on the primary parameters should result in the greatest improvement in kick detection.

One scenario that may yield some important information related to kicks is the use of statistical methods for combining secondary and primary parameters to improve the overall analytical capability of the technologies. Several companies are pursuing this method; however, results are not yet widely available. If it does prove valuable, improving the primary kick detection parameters will certainly lower the KDV.

Improvement of Primary Kick Detection Measurement Leads Directly to Earlier Kick Detection

As inferred from the above discussion about indicators and also the following section that discusses the dynamic use of these indicators, two of the most promising areas to focus on to improve kick detection are the following:

1) Adding[v] flow meters[vi] to the outflow side of the riser. As noted above, the massive size of the mud tanks makes it difficult to improve PVT system measurements; the use of accurate flow meters in effect replaces both the flow indicator and the PVT system from an early detection perspective. In practice, the PVT system is still in place. The PVT system serves as both a backup system and as a way to confirm that the flow meters and trip tanks are working properly and are yielding consistent results.

2) Improving operational procedures such as using more consistent best practices for setting alarms or relying less on flowchecks when there is another positive indication of a kick. Published data on the effectiveness of operational procedures is scarce. However, in lieu of making procedural recommendations, we suggest that the KPIs proposed in this paper be used to measure the effectiveness of operational procedures. It is noteworthy that the effective use of flow meters increases confidence in kick detection to the point where operational procedures can also be improved.

Additionally, for completeness, we note that there have been suggestions of direct kick detection techniques via acoustic (or other types of) sensors, perhaps deployed as part of an MWD system or a static monitoring system. These may one day be an important mechanism for kick detection although the authors are not aware of any of these technologies being systematically used today. As will be discussed, however, flow meters as the primary form of EKD can bring additional benefits for understanding and reacting to what is happening in the well. As just one example, the flow meters can continue to detect kicks even if the fluid in the mud pits is being offloaded or transferred between mud pits. This was described in detail as one contributor to the Macondo accident[vii]. For this and other reasons, we have channeled the technology direction of this paper toward metering, where our analysis indicates the highest immediate value to the industry lies.

Utilization of Outflow Meters. As can be seen from **Table 1**, the incorporation of outflow meters can make a dramatic improvement in the early kick detection equation. For some of the most important cases, the KDV can be reduced by a factor of two or more. The use of outflow meters also introduces another important benefit.

The PVT system does not start recording an influx until the flow enters the pits. There is a delay after the flow enters the flowline before it actually reaches the PVT system. It is not uncommon for this delay to be two or more minutes. For high intensity kicks this is significant; the kick will actually be much larger than what is initially recorded by the PVT system. This uncertainty can be quite large (e.g. 40 bbls for a kick intensity of 10 bbls/min with a 4 minute delay). For this reason we use the symbol “>” in the EKD table to account for this additional volume that is already on the rig but not yet recorded. With outflow meters, the KDV is recorded as it enters the flowline, so this uncertainty is completely eliminated.

It should be noted that the use of some meters on open (e.g. non-MPD) systems introduce some deployment challenges especially if they are retrofitted onto the rig. None of these are insurmountable; here are some of the challenges:

- Coriolis meters require a head pressure to force return fluid through the meter. Although the required pressure is quite low (~3-5 psi) it is still greater than many open return systems can provide, especially at the high flow rates used for the shallower, larger hole sections. In those cases, some type of rotating control device may be required to make it possible to measure outflow.
- Coriolis meters are much more sensitive than PVT, or even trip tank systems. As such, very slight changes such as rig heave or even the manner in which drilling pumps are stopped and started show up noticeably on the meter outputs. Noise reduction techniques such as software that compensates for rig heave and standardized practices on the starting and stopping of drill pumps can improve the consistency of results. When using an open return (e.g. non MPD) system, the use of some methodology of wellbore fingerprinting to characterize outflow transients is essential for helping to positively identify kicks.
- Coriolis meters must be integrated into the rig information system at some level as well as translate the actual meter readings into the output formats typical of the oil and gas industry. Coriolis meter manufacturers rely on third party service providers to deliver workable systems, although some operators have managed this integration themselves.

All these discussions are predicated on the assumption that all the systems are installed, calibrated, and operated correctly by trained personnel. The importance of correct operation cannot be overemphasized. There are cases where large kicks have been taken with flow meters installed on the rig. In each of these cases, either the meter was not working properly, the data was not reaching those who needed to use it, or the people on the rig did not respond appropriately to the data received. In some of these cases, the kicks were detected using the PVT. In others the crews were relying completely on the meters and ignored the PVT with serious consequences. Adequate procedures are important to insure that drilling personnel can readily determine when the meter is calibrated and working properly and when it is not. It is *not* recommended to remove or ignore existing equipment (like the PVT). It is strongly recommended to use all equipment available for kick detection to its full capability.

Combining Inflow and Outflow Meters. Adding inflow meters to the equation brings an additional improvement to the EKD time, primarily due to making the PVT and/or flow meter indications more actionable. In effect, inflow meters remove the uncertainty introduced by counting pump strokes and assuming a constant pump efficiency. If the driller gets a positive indication from a primary indicator, he no longer needs to check the pumps or anything else before taking well control action.

Pumps work remarkably well in general but they do have wear issues that cause efficiency to degrade and there is always the possibility of getting debris in the pumps that lowers efficiency. Pump efficiency is subject to change without notice. The uncertainties associated with inflow measurement using pump strokes and pump efficiency have caused false alarms resulting in reduced confidence in the flow-in versus flow-out measurements. This in turn has resulted in delays in responding to real kicks and influx volumes have been larger than they could have been if more reliable inflow information had been available.

- Installing inflow meters will result in improved precision and increased confidence levels in the measurements so that time is not wasted by requiring secondary confirmation before action is taken. Incorporating inflow data from the cementing unit can also help improve kick detection during cementing and other displacement operations.

Conventional Drilling Operating Modes Associated with Kicks

Drilling Ahead – Deepening the Well. During conventional operations most flow indicators will show large changes in return flow rate but are not quantitatively precise. The PVT will record gains in pit volume if a kick is encountered but must wait until the mud flows all the way down the return line from the riser to the pits to do so. Most rigs require an increase in the pits of at least 10 bbl for reliable detection. As noted above, due to the time lag between the riser and the pits on a floating rig, by the time a 10 bbl gain is detected in the pits, there may actually be a much larger total influx in the wellbore.

If a flowmeter is installed on the return line, then measured flow out can be compared to calculated flow in (based on counting pump strokes) and even very small differences can be detected very quickly since flow out is measured just after the mud exits the riser instead of when it gets to the pits. Although some smaller kicks have been detected, it should usually be possible to detect an influx of 3 bbl or more with a flowmeter.

Making a Connection – Adding a Stand of Pipe to the String to Continue Drilling. The drop in wellbore pressure when the pumps are stopped to make a connection can allow an influx to occur. When drilling with a conventional system the return flow decrease is fingerprinted and compared to a base case run inside casing to allow detecting a change in the profile of that return flow decrease that might indicate a kick. The PVT response is delayed by the time it takes for the mud to run down the return line from the riser to the pits. Wellbore ballooning and breathing can greatly complicate the issue and make it even more difficult to accurately and reliably detect a kick. All these factors combined make it difficult to reliably detect a kick of less than 10 bbl.

When using a return flow meter the return flow rate is measured just as it exits the riser. Not only are the measurements much more accurate, but there is no time lag while the mud runs down the return line to the pits. Using a return flow meter also makes kick detection possible even if the riser boost pump is kept running. Wellbore ballooning and breathing can still exist but they are much easier to identify since the "fingerprint" is more precise. It will still be difficult to detect an influx of less than 5 bbl. This is especially significant since it is during this drilling mode that the vast majority (70%) of kicks are estimated to occur.

We note that when using a Managed Pressure Drilling (MPD) system it is possible to virtually eliminate wellbore ballooning and breathing by not allowing the pressure fluctuations in the wellbore that they require. This can greatly simplify kick detection and make it much more reliable with influx volumes as low as 3 bbl or even less.

Tripping Out – Removing the Drill String from the Well. (Note: Kicks rarely occur while tripping in due to the increased pressure induced by inserting a drill pipe. This scenario is more likely to lead to a loss of wellbore fluid due to surging the formation and this can sometimes lead to a secondary kick.) In a conventional case, the material removed is replaced by mud from a small volume trip tank. Any difference between the volume of material removed and the volume required to keep the hole full indicates either a kick or a loss. Gains of as little as 3 bbl can be reliably measured. The flow indicator can give a relative indication of increases or decreases in return flow rate but most have very limited value. The PVT can be used to confirm the accuracy of these measurements

A return flow meter can be used to measure the outflow rate and compare it with inflow rate when circulating across the riser to accurately measure the volume required to keep the hole full. This volume is then compared to the volume of material removed to detect either a kick or loss, as is done with a trip tank. This technique is sometimes referred to as a "virtual" or "electronic" trip tank. Gains as small as 3 bbl can be reliably detected. The PVT can be used to confirm the accuracy of these volume calculations.

Out of the Hole. This is the scenario when the drill string is out of the hole (e.g. when changing the bit or bottom hole assembly). The wellbore is normally completely static, that is no gains, losses or fluid movement of any kind out of the wellbore. Since the fluid column in the wellbore is static, changes in mud temperature in the hole may result in small changes in volume. As the mud heats up to static formation temperature a very small flow at the surface may result. Therefore an influx of less than 5 bbl cannot be reliably detected. If only the PVT is used then at least a 10 bbl volume will be required to be detectable.

The trip tank can be used with conventional operations to monitor the status of the well while out of the hole. Any influx or losses, even small ones, will be immediately apparent.

If the trip tank is not used, the well can be visually monitored with any flow out indicating an influx. The flow indicator will register high flow rates but has little or no value with the low outflow rates that are being monitored. A gain in the mud pits also indicates a kick. There is a time lag for the mud to reach the pits from the riser and there must be at least a 10 bbl increase for reliable detection.

If the riser boost pump is left running, circulating the riser while out of the hole, then any discrepancy between inflow and outflow rates when using a flow meter will indicate a kick or loss just as when using a trip tank. Even very small kicks can be detected and they are detected much more quickly than when relying on the PVT since the outflow is measured at the riser, not the pits.

Plug and Abandon (Fluid Circulation). Cement plugs are spotted; fluid in the hole may be changed to another density and/or composition; it may be necessary to dump or offload one fluid while pumping another.

In conventional operations, PVT can be used if the pit capacity is such that one fluid does not have to be offloaded while another is being pumped. This makes it possible to measure gains of 10 bbl or more. If it becomes necessary to transfer fluids from or to the active pits during a displacement operation, it becomes extremely difficult to track outflow rates and volumes and to identify a kick by detecting anomalies.

- Volumes pumped by both a cementing unit and the rig pumps must often be tracked and they are usually not integrated into the same data acquisition system.
- Fluids of several different weights are often pumped and spotted or displaced. Expected pressures during various phases of each operation can be used to check to make sure things are going as planned but this can be complicated to do in practice.
- An outflow meter makes it possible to measure the outflow rates and volumes and compare them to calculated inflow rates even if mud is being simultaneously moved into or out of the mud pits. This greatly simplifies tracking actual return volumes and allows detection of kicks as small as 5 bbl.

- If flowmeters are installed on all the mud pumps and the signals from those meters, the meters on the cement pumps, and the outflow meters are all integrated into the same data acquisition system, then accurate flow in versus flow out comparisons are possible regardless of what operation is conducted.

Conclusions and Recommendations

The kick metrics used by the industry today are incomplete. This has the effect of limiting kick database usefulness as far as operational and/or technological improvements are concerned. We have proposed three metrics where data is not consistently available today and recommend that these start being tracked by the industry. The first two are Key Performance Indicators that combine the effects of operational procedures and can help the industry identify practical next steps for improving both kick detection and response while drilling. The Kick Response Time (KRT) and the Kick Detection Volume (KDV) can also be used to evaluate and compare practices and technologies between rigs and operators. A third metric, the Drilling Mode Kick Frequency (DMKF) is significant for understanding the different drilling modes and when kicks are most likely to occur. The estimated rate of 70% of kicks occurring during a "connection" was initially an unexpected result and has the effect of suggesting that effective EKD systems need to be highly accomodative to this drilling mode.

By focusing on "actionable" kick indications and minimizing the Kick Detection Volume (KDV), the path toward early kick detection is clarified: the utilization of outflow meters, when properly installed and calibrated, have significant potential for improving kick detection during drilling operations. Use of these meters with an adequately trained crew can significantly reduce kick detection volumes in three of the five identified modes of operations: making a connection; drilling ahead; and plug and abandon. Metering also improves confidence in the overall kick detection capability so that procedures and alarms can be tuned to reduce the KDV even further.

The proper introduction of an outflow meter could have corrected two important deficiencies that were directly related to the cause of the Macondo accident:

- Earlier kick detection;
- The ability to detect a kick even while mud is being dynamically shifted between mud pits.

While the skilled use of outflow meters (and optionally inflow meters) is perhaps the single most important technology for improving EKD, there are also expectations that improved procedures can have a dramatic impact as well. Whether the method involves procedural improvements, technology improvements, training improvements, or a combination of these, the cumulative effects will be visible in the KPIs. The implication for these KPIs also is not limited to the Gulf but can be used in many different situations including land based drilling. There is no better time than the present to start gathering the KPI data and using this information to systematically improve safety in the Gulf and beyond.

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[i] http://www.bsee.gov/Inspection-and-Enforcement/Accidents-and-Incidents/Loss-of-Well-Control/

[ii] D. Fraser, K. Kubelsky, J. Braun., *An Analysis of Loss of Well Control Events in the Gulf 2007-2013*, currently in preparation.

[iii] "The Chief Counsel's team finds that rig personnel missed signs of a kick during displacement of the riser with seawater. If noticed, those signs would have allowed the rig crew to shut in the well before hydrocarbons entered the riser and thereby prevent the blowout", National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, p. 165.

[iv] *Deep Water Drilling Risk Reduction Assessment*, MIDÉ Technology Corporation, Aug 23, 2010. This report uses purchased SINTEF data using Exprosoft. Kick data from 2007-2009 cannot easily be matched to either the KDV or KRT. We nevertheless used this data as well as guesses from experienced drillers, since public kick data is scarce, to help us approximate the DMKF for different types of drilling modes.

[v] The use of flow meters was also noted in Assessment of Stack Sequencing, Monitoring, and Kick Detection Technology, MCS Kenny report for BSEE, January 23, 2014.

[vi] There are two primary types of meters on the market today: Coriolis mass flow meters and Electromagnetic mass flow meters. Both are excellent and provide order of magnitude improvements in measurement ability over PVT and flow sensors. Also they keep track of the mass (or density) of the material flowing through the meters. Coriolis meters are the focus of this paper since they can be used for both water and oil based fluids, the latter being the most widely used in the Gulf. EM meters only work with water based fluids.

[vii] Deep Water Report to the President, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, January 2011, p. 110.