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The Metrics and Value of Real Time Data: Mitigating Hazards

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Abstract

Historically, the drilling industry has utilized real time data (RTD) for improving drilling efficiencies, documenting occurred events, and reactive decision-making. RTD should promote situational awareness with respect to wellbore instability and hazards. Drilling trends identifiable in RTD change over time as abnormal trends leading to hazards and rarely occur instantaneously. These destabilizing events such as cuttings loading, barrier compromise, kicks, pack-offs, wellbore collapse, or other mechanical and pressure-related causes, whether in rotating or flat-time operations, can be avoided or mitigated. Accepting these hazards as necessary and expected consequences can be a dangerous proposition and denies risk accountability.

Enhancing the systemic approach to *process safety* represents a paradigm shift in the industry. This requires changing behaviors through proactively managing and controlling the pace of the drilling process. A new paradigm suggests the use of a deterministic, physics-based model of real time force-balances in the wellbore during the well construction process. Trends of these forces become predictors of hazards and are routinely identified in many *process safety* failures and consistently result in non-productive time (NPT) and removable lost time (RLT), notwithstanding the large associated costs. The drilling trend behaviors that predict hazards can facilitate leading as opposed to lagging Key Performance Indicators (KPIs). The new paradigm suggested will enable hazards avoidance and thus significantly reduce the costs of drilling. This paper describes and explains these predictive techniques as well as offers suggestions for industry training with respect to surveillance and hazards avoidance using RTD simulators, much as airline pilots would use for continual training.

Introduction

Technology exists to transmit information from a drillsite anywhere in the world. Historically, this data has been used primarily to improve drilling efficiencies in real time or near real time. This RTD can and should be used to promote *process safety*. RTD also falls into the category of Best Available and Safest Technologies[1] (BAST) and therefore has regulatory relevance.

If a wellbore is deteriorating for any reason, it is very unlikely if not impossible, that efficiencies can be applied with any degree of reliability[2]. Wellbore stability must always precede efficiency. A paradigm shift in the industry will be to use RTD effectively to manage wellbore stability, hazards, and risks throughout the drilling process by providing enhanced drilling situational awareness.

To more effectively use this technology, it is important to embrace concepts, such as:

- The insufficiencies and misleading nature of some current and common metrics, such as days versus depth.
- How the industry measures NPT versus RLT and wasted time (WT): If it cannot be measured, it cannot be changed.
- Improve the understanding of *process safety* and know how and why process and personal safety differ.
- The importance of the key physics parameters of drilling; the forces imparted to create the wellbore.
- How effective uses of *pace* and *surveillance* will always save time and money, notwithstanding the issues of regulatory compliance, protecting lives, assets, and the environment.
- *The difference between proactive alerts versus the reactive nature of alarms is a guiding principle of this new paradigm.*

Alerts are proactive, predictive, and raise situational awareness. Alarms, while necessary, can be confusing in RTD systems when set at different levels in different locations or centers, or worse disabled[3]. This important distinction is not unusual in other industries, for example, in Weather forecasting. The Weather service issues Tornado “watches”, akin to an alert when the *psychical* behaviors of the atmosphere are conducive for the formation of a Tornado; atmospheric pressure, wind currents, humidity, and temperature variations. A Tornado warning, or alarm is only issued when an actual Tornado is identified. This is also an analogy to the difference between situational awareness which is proactive, versus an alarm which is reactive.

The Macondo provides an excellent example of an application related to alarm deficiencies. It is clear that the general alarm and other alarms had been bypassed, disabled, or were dysfunctional. There is no evidence that alarms had common settings, nor was there a common philosophy for engaging alarms.

Excerpt 1: BP Macondo, Various Testimonies and Statements Regarding Alarms

In testimony: "After the gas release created a jolt and a hissing sound, when mud was seen coming out of the diverter, generally just before the explosion, some heard the first alarm only after the first explosion, and others only after the general alarm, which was in manual activation mode and was manually activated after the second explosion."

Q. Is there any reason you would not want the general alarm to be set off automatically when an alarm went off on a panel?

A. Yes. The reason why it doesn't automatically, instantaneously go off is, these alarm sensors are fairly temperamental. You know, any number of things can set them off prematurely, and then we have vast experience of that, you know, fog set them off, pressure washing, just deterioration, you know. These alarm sensors are prone to going off, waking people up at 2:00, 3 o'clock in the morning for false alarms. It's bad for safety, you know. Disrupting people's sleep needlessly, that's the main premises behind the general alarm.

RTD should promote situational awareness with respect to wellbore instability and hazards. Drilling conditions happen in trends over time, rarely instantaneously. Trends also build over time and RTD key data tracks reflect those trends. Wellbore stability is governed by external factors, bounded by the quintessential pore pressure and fracture gradient forces at depth, both of which determine the safe drilling margin. These earth forces are always difficult to measure with precision, occurring in trends over time. When these external forces change, including lithological changes, physics demands that the forces imparted on the wellbore also change to retain wellbore stability and to sustain proper barrier control ($\Sigma F=0$ depicted in **Figure 1**).

RTD dynamics or forces are best holistically represented by **Figure 1**. In that regard, the borehole is simply a hydraulic cylinder that is being extended (or maintained) in real time by counter-balancing forces. Governing physics and engineering principles are themselves always certain. To maintain proper wellbore balance, the *drill system forces* must always counter *earth forces* without compromise. The physics principle are objective and deterministic. Reliability is not achieved through empirical or probabilistic statistics or reliance on deviations from the mean of a single-track data trend. Rather, reliability is achieved through the convergence or divergence of a combination of effects representing the input *drill system forces.* Convergent and divergent behaviors in critical RTD tracks will be discussed in case histories.

Successfully navigating the safe drilling margin between pore pressure and fracture gradient requires *pace* and *surveillance* in that it takes time and scrutiny to:

- Engage multidisciplinary teams in interpretation of the RTD.
- Ensure a controlled drilling rate of penetration that effectively cleans the wellbore to avoid issues such as cuttings loading.
- Manage gas levels to maintain the integrity of the primary mud barrier.
- Ensure the primary barrier is effective and changes as needed to maintain a proper force balance, whether conventionally or enhanced with *controlled pressure drilling*.

As drilling complexity increases globally, the robust uses of RTD require multidisciplinary collaboration. In narrow margin drilling conditions such as deepwater and high pressure, high temperature (HPHT) environments, the pore pressure and fracture gradient dynamics will always be imprecise, and subsurface stresses create additional force vectors that add to this uncertainty. These stresses are always reflected in drilling trend forces but not necessarily recognized in the geophysical data predictions. Pore pressure and imposed stress levels can be quite different in magnitude. Proactively recognizing these differences manifested in RTD trends is critical to wellbore stability and essential in managing the safe drilling margin.

The outdated notion in the industry that RTD should not control or influence operations must be dispelled. A new model or paradigm must be embraced. In today's world of information technology (IT), an RTD model can be built that:

- Progressively elevates situational awareness and minimizes the inconsistencies (and nuisance) of reactive alarms.
- Fully utilizes IT to engage the right people at the right time.
- Utilizes software that provides situational awareness and optimizes organizational capability while alleviates strained resources.
- Provides simulated training, much like the airline industry. Training that is focused on wellbore stability and well control avoidance, not just early kick detection and reactive well control.
- Suggests corrective actions for wellbore stability assurance.

To change the current model to one of robust, interactive, and effective use of RTD, common industry metrics must also be questioned and improved. KPIs could be primarily leading, not lagging, indicators. Personal safety has improved dramatically through behavioral-based safety programs using leading indicators. The same philosophy must be extended to RTD and process safety assurance.

The industry must be convinced there is a need for change; that is, what is in it for the industry. To that end, the industry could benefit from saved time, money, the environment, and most important, saved lives. Currently, the industry sometime feels that due to the well costs, it is important to drill as fast as possible. *It is more important to drill reliably*, which in turn ensures the best possible result, including costs. It always pays to *stop, look, and listen*.

Notwithstanding the direct benefits of reducing costs, the industry must also consider our license to operate, granted by the public[4]. One case history herein investigates a catastrophic near miss that easily could have resulted in consequences potentially on the scale of Macondo.

Industry standards regarding monitoring RTD would also help ensure that regulations are effective. The more proactive the industry is in establishing a common set of standards for data and monitoring, the less the necessity of regulatory involvement. Elements of the industry have historically resisted developing these collaborative standards, primarily fearful of losing a competitive edge. This attitude marginalizes *process safety*. Ensuring *process safety* is fundamental to industry viability and ultimately its public-granted license to operate.

Personal Safety and Process Safety

The definitions of *personal* and *process safety* are different, but can have similar consequences. *Personal safety* has to do with avoiding harm and injury. **Figure 2** depicts the significant advances made in the industry with respect to personal safety.

Figure 3 and **Figure 4** indicate that personal safety improvements have not translated to *process safety* improvements. *Process safety* must be recognized as a comprehensive systems process and use leading KPIs that promote *process safety* behavioral improvements. RTD can become the engine to generate these KPIs by way of developing performance indicators that are proactive, using alerts that raise situational awareness.

The most fundamental definition of *process safety* is that of ensuring containment, the loss of which is merely the outcome of a failed *process safety* system.

As defined by Dr. Robert Bea, "*Process safety* is the proactive, interactive, and reactive integrated continuous processes whose goal is prevention and mitigation of major disasters involving complex engineered systems"[5].

Process safety is quite different in definition and scope than personal safety as depicted by **Figure 5**. *Process safety* includes worker safety as *merely* one element of the total requirements of a *process safety* system.

To ensure *process safety*, operators need the following:

- Organizations that collaborate, such as geosciences and drilling.
- Hardware and wells designed to meet maximum operating conditions criteria in the prescribed environment.
- Environments and technologies that support collaboration, including RTD systems.
- Procedures that recognize, manage, and mitigate risks.
- Structures that support collaboration.

Drilling organizations cannot operate safely, reliably, and effectively in isolation. If designed properly, RTD systems offer situational awareness on collaborative platforms that enable proper interface of all the elements necessary in a *process safety* system outlined by the Five C's[6] as defined by Dr. Bea.

1. Commitment: top down and bottom up

RTD can only grow bottom up when it is planted, modeled, and enforced top-down.

2. Capability: technical and management abilities

An RTD-driven *process safety* system can and will notably influence training for both technical and management personnel.

3. Cognizance: awareness of hazards and risks

RTD enables the application of leading KPIs necessary to improve performance, reliability, and *process safety*.

4. Culture: balanced production and protection

Addressing the culture can be especially difficult, especially overcoming a dilemma called willful blindness. Paraphrased: "Willful blindness is what we could know, what we should know, but somehow manage not to know"[7]. *Process safety* failures are frequently relegated to anomalies and willful blindness often creates the denial of "it cannot happen here".

5. Counting: valid quantitative recognition of production costs and benefits

Counting, or metrics, is the key to changing or influencing the current models for drilling operations. The way we count drives behaviors such as expediency and cost cutting. While saving money is advantageous, cost cutting at the expense of ensuring *process safety* demonstrably leads to financial loss. Executing operations with *pace and surveillance* using RTD to ensure *process safety* actually saves money, and the proof is in the metrics.

Advantage of Utilizing Leading versus Lagging KPIs

Generally, key drilling metrics are categorized into productive time (PT), non-productive time (NPT), and removable lost time (RLT).

PT in essence is time spent on the critical path while making progress. NPT is generally considered as time off the critical path for various reasons. RLT consists of improving efficiencies and eliminating wasted time (WT) resulting in unnecessary operations divergent from the critical path. It is impossible to apply and sustain efficiencies in an unstable wellbore. Typically current RTD systems deal with efficiencies with some competence. However, when wellbores show signs of instability these systems do little to identify, influence, avoid, or eliminate WT.

Addressing WT with avoidance, improvements, training and facilitating *process safety* yields substantial benefits. *The industry is leaving an enormous sum of money on the table and an RTD system devoted to process safety can and will mitigate that problem. The metrics of our drilling practices prove it.*

Spending time projecting hazards-related costs and estimated WT is fine for AFE purposes and budget estimates. However, these projections and estimates fail to consider operational realities and dangers by ignoring, accepting, or even inducing hazards as they evolve.

It is important to recognize a hierarchy of drilling-induced hazards, which can be portrayed as follows:

Table 1: The Progressive Rotational Hierarchy of Induced

Well Control[8]

Failure to clean hole →Excess equivalent circulating density (ECD) creates ballooning →Misread → Add weight → Induces losses → Column recovers with gas → Kick, bubble, and well control

Once a well destabilizes, WT begins and accelerates as the consequential hierarchy evolves. Trend alerting, noted in case histories, provides the platform and means for situational awareness and suggests where rational, proactive, collaborative team decisions should be engaged.

Many industry metrics represent lagging indicators, counting events after they occur. It is important to capture this data and analyze these events. Future awareness is critical for planning and avoiding hazards. Lagging metrics however are not leading KPIs and they are less useful in improving performance and reliability. Much has been said and written regarding early kick detection and well control. Even though early kick detection and executing well control is crucial, these well control metrics are nonetheless *lagging indicators of events that have already occurred. What is essential is to consistently tracking trend behaviors that proceed and predict kicks and other hazards.*

A learning and training system derived from RTD provides the basis for leading KPIs. That is accomplished by tracking improvements over time in hazards avoidance metrics driven by alerts and progressive improvements in WT.

An alert system based on the primary forces imparted on the wellbore in response to changing wellbore conditions (earth forces vs. drill systems forces), elevate awareness of early kick detection and other hazards to a new level in that an awareness of behaviors of the changing forces become predictive, establishing leading KPIs when consistently tracked.

Each case history herein will identify the WT that actually occurred as a result of progressive and predictive wellbore instability.

Defining Pace and Surveillance

Pace and surveillance are both technical in nature and philosophical in intent. *Pace* can literally mean that drilling operations proceed at a controlled rate to ensure wellbore cleaning and avoid cuttings loading and at a *pace* that can ensure validation of material balance through critical barrier displacement cycles. These are technical in nature and must also enable *surveillance*; engaging stakeholders for collaborative solutions. In Case History 1, the projected Measured Depth-Toe of a horizontal well was nearly achieved. The borehole was clearly at risk, yet drilling continued to attempt to meet the projected target depth. The result was a collapsed hole, stuck pipe, and loss of the entire horizontal section. The geoscience team indicated that had they known the wellbore was at risk, they would have simply accepted the achieved current depth, stabilized the wellbore, and set casing. It can also be assumed that they might have made a different decision, but that misses the point of *surveillance*. It is about the team having the opportunity to make a different, better, more informed decision. This kind of collaboration saves money and avoids WT.

A question the industry should ponder, “If a pilot greeted the passengers at the door and stated that he was the best pilot ever, and intended to take off, fly, and land exactly how he wished, would one get on get on that plane?” Airlines use flight path information and air traffic control (ATC) to guide us to safety. In fact, they use that same information to optimize speed and altitude to take advantage of the best wind currents, yet air traffic control, not the pilot, will not hesitate to reroute in the face of danger: *pace and surveillance*. In fact, ATC uses alert systems very similar to those proposed herein; driven by predicting hazards, not alarmed reaction to hazards that have already occurred.

The drilling industry can and should do this with robust *process safety*-driven RTD systems that have the ability to control *pace and surveillance*.

RTD to Enhance Training: Optimizing Strained Resources

In the industry there are two issues driving behaviors that are ever present; the fear of slowing operations and that the rig personnel always know best. While perhaps true that the rig and operator supervisory personnel might be exceptional, reliance on line-of-sight decisions alone without collaborative team input proves disastrous and wastes money. The way to change this behavior is by recognizing that current drilling metrics lack indicative value useful to facilitate or even encourage controlling operations through *pace and surveillance*.

Part of the challenge is answering the question, “Would the results have been different with collaborative real-time analysis and slowed operations?” The short answer is that we do not know. What we do know, as evidenced in the case histories, is that continuing to drill, trip, and displace (any flat time) in a disintegrating wellbore leads to counterproductive consequences. Even minimal consequences negatively impact the drilling cost curve and waste money. The industry should eliminate line-of-sight decisions based on expediency.

Situational awareness alerting must be made to all stakeholders at a consistent level and in real time to effect the best solutions. Another question must be asked and answered, “Can we afford to ‘chain the brake’ and wait on better collaborative, multidisciplinary team decisions?” Considering the case histories metrics, the question should be, “Can we afford not to ‘chain the brake’?” Based on the added cost portrayed in the case histories, the answer is a resounding yes. We can afford to “chain the brake”, but only with *surveillance* and controlled *pace*. Will the drilling team stakeholders always make the right decisions? More often than not they will make the correct decisions, especially as real time simulated training becomes reality.

The industry has abundant well-control schools and simulators. While necessary, well control is purely reactionary. Simulated RTD training should also promote and coach, avoiding well control issues and other hazards.

The authors’ proposed developmental cycle of a *process safety*-driven RTD system uses actual Well Site Information

Transfer Markup Language (WITSML standard) data for simulated training and alerts for awareness that trigger best practices and suggested corrective actions. The industry has devoted an enormous amount of resources to massage empirical data. Big data must be relevant data. Cased-based reasoning could be valid, but only as it applies to corrective actions taken on comparable wells.

The fear is that empirical data derived from *big data* will exclude wells as illustrated in Case History 2, wherein the well was the fifth in a series of developmental wells. The blowout, while brief, most assuredly was a spark away from catastrophic sour gas release. Yet, the common sentiment from interviewees was that no offset well had encountered the same problem, so it was *assumed* that drilling could continue using the same practices. The RTD clearly indicated an impending hazard long before it occurred. This case history illustrates that the physics of force balance in a wellbore are deterministic and should not be compromised by empirical data that will drive questionable assumptions, decisions, and behaviors. As stated by Dupriest, et. al.

Excerpt 2: Deterministic Physics and Digital Data[9,10].

"A performance strategy that changes the way the work is done must also consider other issues. Many real-time decisions are made at the brake handle. Drillers must be provided physics-based training or they cannot implement new physics-based practices.

Statistical methods have been used to great advantage to improve product quality or job execution. They identify non-compliance or variability. However, a deterministic understanding of how things work, coupled with the appropriate data collection and display, provides the team the type of unique viewpoints that can result in more fundamental changes in how the work is done, which yields greater changes in performance."

…. "Workflows that deliver physics-based training, real-time recognition and response, risk management, and management support for change are essential. Digital data strategies must support these activities"

and…

Differentiating performance starts by first developing a deterministic understanding of the physics of your limiter…. In contrast, companies that optimize based on historical practices are designing to avoid the historical causes of failure and not to fundamentally change performance. *Differentiating performance starts by first developing a deterministic understanding of the physics of your limiter and then developing new practices based on that understanding*".

The industry operates with strained resources and training. This is not new, but nonetheless problematic. A question frequently asked is, "Where is the industry going to train and find the kind of experience needed for remote center operations?" *The answer on a global scale: It is not possible nor is it necessary with a physics derived, deterministic RTD system built to ensure process safety.* In that regard, a system similar to that which the air traffic control uses is necessary in our industry. In the United States there are no requirements that an air-traffic controller have aircraft pilot experience.

Excerpt 3: FAA Comments on Air Traffic Control[11]

"Every day of the year, and especially on holidays, more than 15,000 federal controllers at 315 FAA air traffic facilities are on the job, guiding more than 87,000 flights every day across our national airspace system.

"To be an Air Traffic Control Specialist, you must:

- Be a United States citizen
- Start at the FAA Academy no later than your 31st birthday
- Pass a medical examination
- Pass a security investigation
- Have three years of progressively responsible work experience, or a Bachelor's degree, or a combination of post-secondary education and work experience that totals three years.
- Pass the FAA air traffic pre-employment tests
- Speak English clearly enough to be understood over communications equipment"

An RTD system engaged with alerts for conditions indicative of imminent instability is attainable and being designed. The intent of an alerting system is to provide the necessary lead time to involve the right personnel at the right time. *That does not require exceptional drilling experience in remote centers to be effective.*

Case Histories Driving the Business Cases for Pace and Surveillance

Proprietary software was used to apply the following process to WITSML RTD gathered on wells from various operators in diverse global locations and environments:

- All data was *sterilized* to protect operator identity if necessary or requested.
- Key data tracks are organized and analyzed.
- Data is overlaid in normalized, dimensionless scales in drill-down fashion to enable recognition of trend behaviors.
- Appropriate trends identified with respect to predicting potential hazards such as stuck pipe, losses, and kicks.

- WT was identified and derived from daily drilling reports. Wasted costs estimates based on general costs for a given locale or environment.

Operator daily drilling reports were used to compare actual events to the RTD predictions. The following case histories discuss these outcomes and offer suggestions and insight to predicting events by way of real-time trends and why failure to recognize emerging trends resulted in the actual wasted-time events.

In the following case histories there is a common solution: A robust, *process safety*-driven predictive RTD system could recognize the alert conditions and annotate suggestions for stability solutions, In short: *stop, look, listen, and engage*. A few hours of prevention saves lives, the environment, and literally billions of dollars. *Had the RTD trends been alerted and attended, each case history incident was entirely avoidable.*

Case History 1: Loss of Horizontal Well Section at Near-Toe

Case History 1 represents a horizontal well drilled into an underbalanced state. The well was very close to the projected toe of the horizontal section.

Figure 6 depicts a horizontal, unconventional shale well. A summary of progressive RTD is as follows:

1. At +/-17,750 ft., pump pressure trends began decreasing.
2. Flow out spiked and flow gains were indicated.
3. The pump rate was increased and flow correspondingly increased.
4. Torque increased.
5. Drilling continued and the wellbore ultimately collapsed.

Result: Collapsed wellbore, stuck pipe, lost bottomhole assembly (BHA), and the horizontal section lost. WT: Three days with stuck pipe, plus 13 days to sidetrack and redrill the horizontal section. This wasted time (WT) could have been avoided.

Fact: The signatures of impending stuck pipe were evident.

Solution: A robust, *process safety*-driven RTD system to recognize the alerts conditions and annotate suggestions for stability solutions, such as stop and circulate, proceed at a controlled pace, increase ECD, or other options could be suggested. This is also a case where collaboration with the geoscientists would have proved valuable. In interviews, the geoscientists indicated that had they known the well was experiencing problems at this near-complete MD, they would have reconsidered the projected depth requirement. This kind of recognition is also important to *process safety*. The incident was predicted in the RTD, and thus avoidable.

Estimated CAPEX cost: $1,600,000 direct, plus tools and service.

The continuing costs of the wells and development of the project was deferred, and that was at $100+/barrel. With current prices, it is still on hold.

Case History 2: Blowout in Horizontal Drilling

Case History 2 represents a near-miss blowout that could have been catastrophic. The situation surprised the entire drilling team, although a few raised concerns while drilling. The standard sentiment (paraphrased from interviews) consisted of: ‘this is the fifth well in a series of developmental wells and this has never happened before. Fractures do not flow.’

Figure 7 represents a case history of a horizontal, unconventional shale well. A summary of progressive RTD is as follows:

1. At +/-16,900 ft., differential pressure and pump pressure began decreasing.
2. Simultaneously, gas peaks on connections were increasing.
3. Time for gas to drop out on connections was also increasing with upward trend spikes on flow rate.
4. Drilling continued.
5. ***At +/-17,050 ft., the seal on the rotating control head failed with over 280 psig. Sour gas and raw condensate blew over the derrick.***
6. ***The BOP sealed before the dangerous flow stream ignited.***

A natural fracture will flow if it has transmissibility; it is a matter of degree and quality of the fracture. The RTD had early warning signs of failure long before the event occurred.

Result: Near miss. WT: Over six (6) days were required to re-establish wellbore stability. This WT undoubtedly could have been avoided.

Fact: The signatures of an impending, induced kick as a result of rapid drilling with inadequate circulation were evident at least four drillstring connections prior to the incident.

Solution: A robust, *process safety*-driven RTD system to recognize the alerts conditions and annotate suggestions for stability solutions, such as stop and circulate building gas out of the system, proceed a controlled pace, increase ECD, or other options. A few hours of prevention would have saved a near catastrophic miss and *the six days* WT.

Estimated CAPEX cost: $600,000, plus cost of sidetrack.

Case History 3: Driller-induced Stuck Pipe

Case History 3 is a vertical well that at a tour change of rig personnel, the weight on bit (WOB) was arbitrarily doubled to drill faster. Prior drilling had been steady-state and uneventful until that time.

Figure 8 represents the vertical well with the following progressive RTD:

1. Drilling had been routine and steady-state.
2. At tour change, the WOB was almost doubled.
3. The torque trend increased dramatically.
4. ROP doubled, but pump pressure began to inordinately trend upwards and spike: cuttings loading and insufficient wellbore cleaning occurred.

5. Cuttings loading supported by increased fluid loss and a dramatic increase in the expected volume of cuttings.
6. Drilling continued.

Result: Stuck pipe, fishing, lost BHA, lost hole section, and sidetrack. WT: More than two weeks.

Fact: The signatures of all drilling conditions support the lack of wellbore cleaning as a result of fast ROP.

Solution: A robust, *process safety*-driven RTD system to recognize the alert conditions and annotate suggestions for stability solutions, such as stop and circulate, proceed at a controlled pace, decrease the ECD, or other options could be suggested. A few hours of prevention would have saved two weeks WT and a sidetrack.

Estimated CAPEX cost: $1,400,000 direct, plus tools and service

Case History 4: Flow While Displacing: Blowout

Case History 4 reflects vast improvements needed in real-time systems; that is, RTD systems built on the premise of *process safety*.

Figure 9 depicts fluids displacement in a deepwater well, preparing for temporary abandonment. A summary of progressive RTD is as follows:

1. An inconclusive negative test on the cased wellbore had been conducted.
2. Displacement of the primary mud barrier to completion fluids was initiated.
3. The RTD discrepancies in real-time data trends clearly indicate an unstable cased wellbore long before the blowout occurred.
4. Alarms were turned off, and set “on manual”[12].

Result: Catastrophic blowout, loss of lives and assets, and environmental spoilage. WT: Uncontrolled flow for over 90 days.

Fact: The signatures of numerous abnormal data trends were apparent from the initiation of displacement. Notwithstanding the loss of lives and still unknown long-term environmental consequences, from a cost perspective alone, it is highly unlikely that this WT and costs can ever be recouped from any efficiency improvements derived in deepwater, not just from a single company but from the industry as a whole.

Solution: A robust, *process safety*-driven RTD system to recognize the alerts conditions and annotate suggestions for stability solutions, such as stop and validate material balance of fluids and re-evaluate pressures. ***Had the RTD trends been alerted and attended, this incident was entirely avoidable.***

Estimated CAPEX cost:

- $60,000,000,000+ direct, plus tools and service
- Offset “relief” wells
- Environment: Unknown
- Other industries: Unknown

Case History 5: Deepwater Induced Kick, Lost hole, Sidetrack

Case History 5 depicts a deepwater well wherein fast drilling in very soft shale resulted in cuttings loading and an ECD trend above the safe drilling margin that exceeded the leak-off pressure of the previous casing seat. The primary barrier was eventually compromised and the wellbore column recovered with a drilling-induced kick.

Figure 10 represents a deepwater well whose summary of progressive RTD is as follows:

1. At +/- 12,200 ft., the ECD began to trend upwards after very rapid ROP: Cuttings loading
2. The operator applied a wellbore cleaning sweep and continued with an ROP too fast to clean the hole.
3. Gas levels were building in the hole. At 13,200 ft., the ECD began to reverse with fluid losses. The ECD was already above the leak-off test (LOT).
4. The wellbore was fractured and the primary barrier was compromised. The wellbore fluid column recovered with a kick.
5. With the wellbore fractured and in an at-balance situation, the ECD was too low to counter-act the pore pressure, yet too high to avoid massive fluid losses.

Result: Well control, stuck pipe, and a packed-off drilling string; an exceptionally dangerous dilemma. These conditions resulted in over 11 days needed to stabilize the wellbore and fishing, plus materials and cost to sidetrack. Additionally, the sidetrack casing setting depth was over 1,600 ft. above the original planned depth, resulting in wasting a casing size to total depth.

Fact: The signatures of cuttings loading as a result of exceptionally fast ROP were evident for at least 1,000 ft. of drilling prior to the incident. Drilling continued and key parameters were ignored. The geoscientists later complained that drilling was so fast that there was not enough time to analyze and collaborate on the data.

Solution: A robust, *process safety*-driven RTD system to recognize the alerts conditions and annotate suggestions for stability solutions, such as stop and circulate gas out of the system, proceed at a controlled pace, decrease ECD, or other options, including setting casing. Additionally, a proper alert system would notify when the ECD was at or near the safe drilling margin. A few hours prevention would have saved a near catastrophic miss, not to mention the 12 days of WT This incident in terms of deepwater operations was avoidable, cost over $ 20,000,000 US, and was all unnecessary.

Estimated CAPEX cost: $20,000,000, plus relief wells, loss of assets, lives, and yet to be determined environmental damage.

Case History 6: Underbalanced Well, Collapsed Hole, Sidetrack

Case History 6 describes a situation where the wellbore entered the reservoir after achieving the build angle.

Figure 11 represents an underbalanced, collapsed wellbore whose summary of progressive RTD is as follows:

1. Standpipe pressure was increasing at constant pump rate: indicating possible pack off/hole collapse.
2. Gas levels were increasing significantly.
3. Motor differential pressure and torque began increasing simultaneously.
4. Gain/loss rates and flow increased.
5. Wellbore stability disintegrated after +/- 2,400m.
6. Drilling continued and induced losses, the primary barrier was compromised and a kick ensued.
7. The wellbore collapsed at 2,500m.

Result: Stuck pipe and a lost BHA. The well was abandoned 45 days later. The WT was avoidable had casing been set at the "at balance" point.

Fact: The signatures of transitioning into higher pressures and wellbore instability were evident as early as 2,300m.

Solution: A robust, *process safety*-driven RTD system to recognize the alerts conditions and annotate suggestions for stability solutions, such as stop and engage the geoscientists and evaluate the transition zone before the stuck pipe incident occurred. At a minimum, stop drilling and evaluate the untenable balance in the inability to properly apply mud weight and ECD.

Estimated CAPEX Cost:

- $4,500,000, plus added casing, tools, and services
- Even at previous prices of $ 100/barrel the drilling program was delayed and remains so.

The Historical Cost of Business as Usual Based on Case Histories

The industry must determine how long drilling as usual can be sustained, especially in environments such as unconventional horizontal shale, which are often economically marginal. One failure can negate an entire drilling campaign. Case History 1 is an excellent example. Each case history represents failed economics wherein a bit of *pace and surveillance* would have at the minimum significantly mitigated, if not eliminated the higher consequences of failure demonstrated.

The industry needs to look no further than the Macondo wherein RTD, had it been analyzed and more importantly, alerted, would have unquestionably saved billions, not to mention lives, assets, and the environment. The signatures of pending catastrophe, the predictive alerts, were without a doubt present. It is not the intent herein to detail a catastrophic incident, rather to focus on risk that can be mitigated with a *process safety*-driven RTD system. Case History 5 illustrates how risk in deepwater is also driven by well complexity, creating a more compelling argument for mitigating risk through *pace and surveillance*.

The industry must never lose sight of the fact of the possibility of a catastrophe occurring again, where loss of life and damage to the environment and the industry's repetition occurs. Case History 5, **Figure 10** represents a deepwater well where WT exceeded 11.5 days, plus a sidetrack. Considering Case History 2, while in a much different environment, would the consequences be any less if sour gas penetrated a residential neighborhood or a school yard?

The industry must realize that drilling at a rate of expediency versus the speed of ensuring *process safety* not only costs money for the least of consequence, WT, but can in fact be catastrophic in any environment.

Pace and surveillance always pays on any well, anywhere, by any operator. *Stop, look, listen, and engage*.

The Positive Impacts on the Regulatory Environment

The industry in general has an innate aversion of regulations which varies by location. It is not the intent of this paper to argue the pros and cons of regulations, just to state that what is most needed is effective regulations and that the more the industry ensures *process* and *personal safety*, the less likely to have regulatory intrusions or even new regulations, such as those created in the wake of the Macondo catastrophe.

A study of US regulations reveals complexity, yet the regulations are simple in principle. The simplicity has two symbiotic paths: *process safety* through ensuring design and barrier maintenance, and compliance most notable with respect to Personal Safety. In February 2014 a strategy report for BSEE was published by 838 Inc., titled "An Assessment of the Various Types of Real-Time Data Monitoring Systems Available for Offshore Oil and Gas Operations". This extensive 220 page report reflects many of the issues and ideas discussed with BSEE and other regulatory bodies (N. Sea, etc.) by the authors of this paper from 2011 thru 2013 depicted in **Figure 12**.

Using RTD can positively impact the regulatory environment and simplify reporting and compliance. This produces a more effective and efficient partnership between regulators and operators by promoting *process safety* and mitigating operational risk.

RTD systems must support controlled and collaborative outcomes as successful as those used in the airline industry. In the airline industry, there is no room for individual use of personal discretion to decide on matters related to how, when, and where to takeoff, fly, and land an aircraft. These types of individual, line-of-sight decisions are chaotic and dangerous. Robust *process safety*-driven RTD systems can improve and simplify regulatory compliance and reporting and instill some industry standards with respect to monitoring or *surveillance* operations.

The new paradigm of *process safety*-driven RTD systems should include the time-saving benefits and costs of compiling reports in real time such as BOP testing, tubulars, barrier removal and displacement, safe drilling margin maintenance[13], and all critical requirements of current regulations (**Excerpt 3**). Operational tool limitations and boundaries could also be alerted for issues such as pressure ratings on downhole tools and other bounding safety factors. Each of these elements need not be embedded in the real-time dynamic data, but could co-exist as "plug and play" modules.

Excerpt 4: BSEE and the Safe Drilling Margin

§ 250.414 What must my drilling prognosis include?

(c) Planned safe drilling margin between proposed drilling fluid weights and estimated pore pressures. This safe drilling margin may be shown on the plot required by § 250.413(g);

§ 250.427 What are the requirements for pressure integrity tests?

(b) While drilling, you must maintain the safe drilling margin identified in the approved APD. When you cannot maintain this safe margin, you must suspend drilling operations and remedy the situation.

The safe drilling margin is not static. It is subject to the uncertainties of pore pressure and fracture gradient, BSEE regulations, and other regulatory agencies such as NORSOK[14], clearly identify that once a safe drilling margin cannot be maintained the operator is required to suspend drilling operations and "remedy", not merely notify. In this regard, a *process safety* RTD system can predict when this level is attained, in an automated fashion, by way of trend alerting. This is demonstrated in **Figure 10.**

Embracing the inevitability of RTD with capabilities beyond the scope of conventional systems will be a benefit to operators, not a hindrance, and provide a more cooperative and transparent venue for regulator, operator, and contractor collaboration.

Conclusions

RTD utilized by collaborative drilling teams offers the opportunity to significantly improve financial performance, efficiency, and ensure reliability in the holistic drilling processes. RTD is a key element of a robust *process safety* system in detection, predictions (heretofore an unexploited capability in conventional well telemetry software systems RTD), and mitigation of hazards to improve Removable Lost Time (RLT) and thus reduce costs. The industry has used RTD primarily to improve efficiencies, but hazards' anomalies that occur are primarily recognized by after-the-fact alarms. The force balance of a wellbore is a detectable principle of physics and drilling trend-forces become predictors of hazards. It is critical to realize that this type of predictive capability is proactive with respect to hazard mitigations such as fluids losses, kicks, and other hazards. Accepting those hazards as inevitable and merely detecting them upon occurrence is reactive, costs money, and invites dangerous situations as the Macondo and a hosts of other examples proves.

Routine use of RTD and engaging multidisciplinary surveillance teams as protocol while controlling the pace of drilling operations requires a paradigm shift in the industry. This also requires establishing standards of inter-industry collaboration and cooperation on RTD within the regulatory framework. The shift cannot occur without engaging the "Five C's"[15] and that requires top-down management commitment. RTD can be used as a key element of a *process safety* system. Stop, look and listen always saves money, not to mention lives and the environment. Industry understanding and acceptance of what *process safety* means is fundamental to a step change in the industry. A loss of primary barrier, well control event, or loss of well control is the consequence of a *process safety* systemic failure, not merely a breach of *process safety*. *Process safety* is fundamentally different from personal safety, but also needs behavioral-based attributes that have been so instrumental in improving personal safety in the industry. Therefore, the industry must revise its metrics and begin to rely on behavioral leading, not lagging KPIs. Personal and *process safety* simply cannot be treated the same in that *process safety* is the "proactive, interactive, and reactive integrated continuous processes whose goal is prevention and mitigation of major disasters involving complex engineered systems[16]".

Finally, as an industry, we must ask and answer why there are no uniform drilling standards with respect to RTD especially when other key industries have had effective telemetry processes in place, having embraced *process safety* and leading KPIs for decades. As drilling complexity continues to increase and experienced resources dwindle, the time to employ and engage robust RTD-driven *process safety* systems is now and it is imperative that new RTD models currently in design are embraced with top-driven management passion.

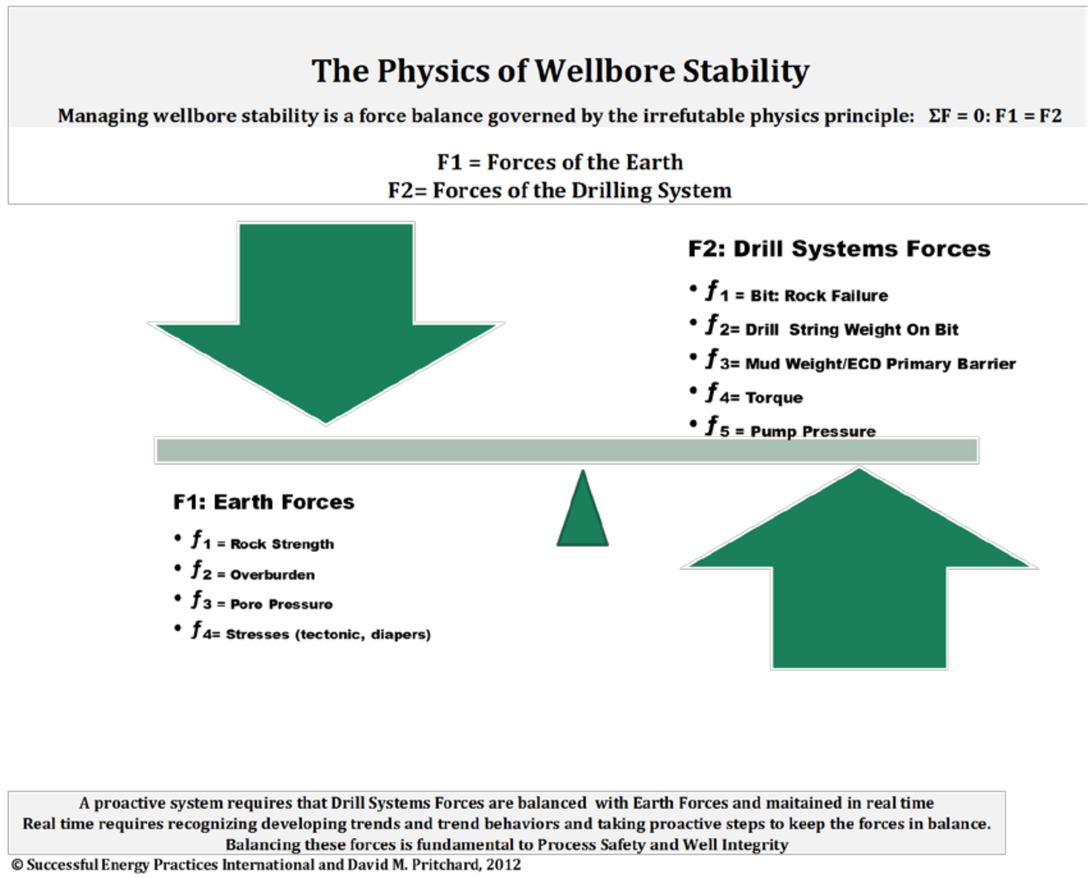


Figure 1: The Physics of Wellbore Stability[17]

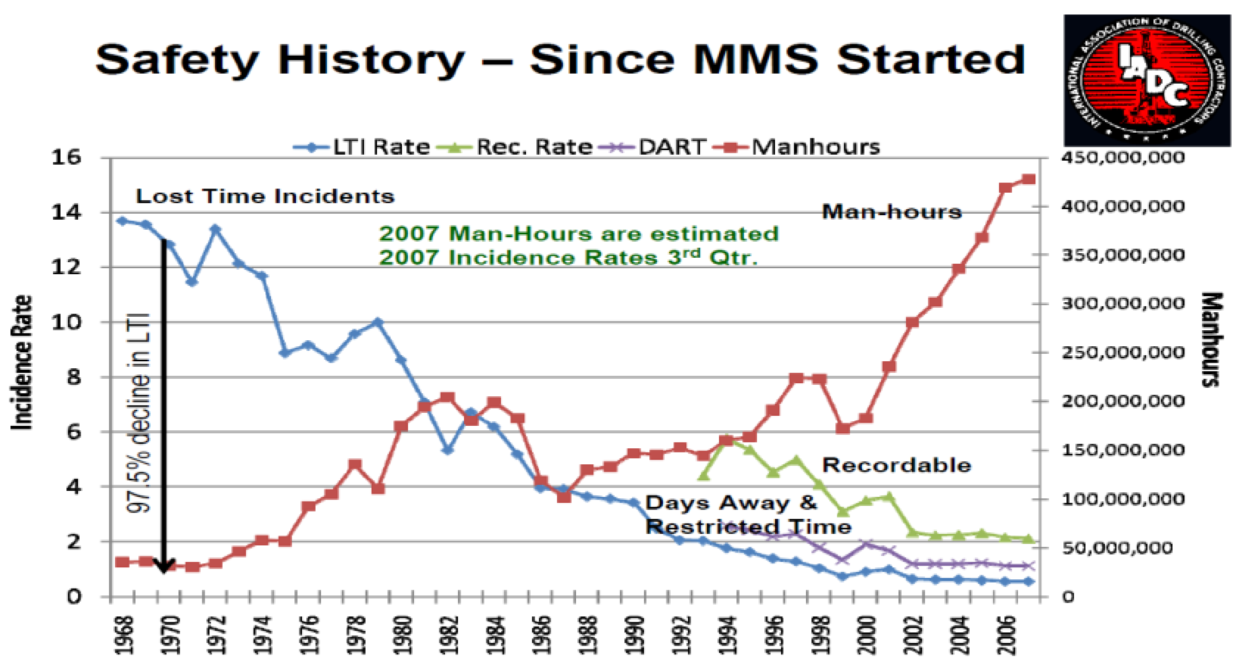


Figure 2: MMS Personal Safety History through 2006[18]

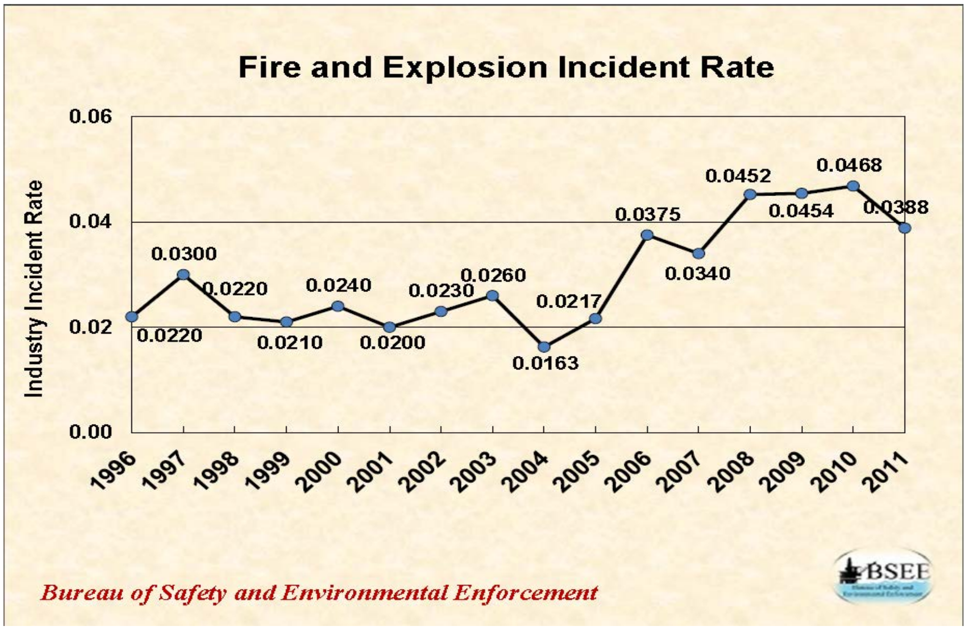


Figure 3: BSEE Fire and Explosion Incident Rate

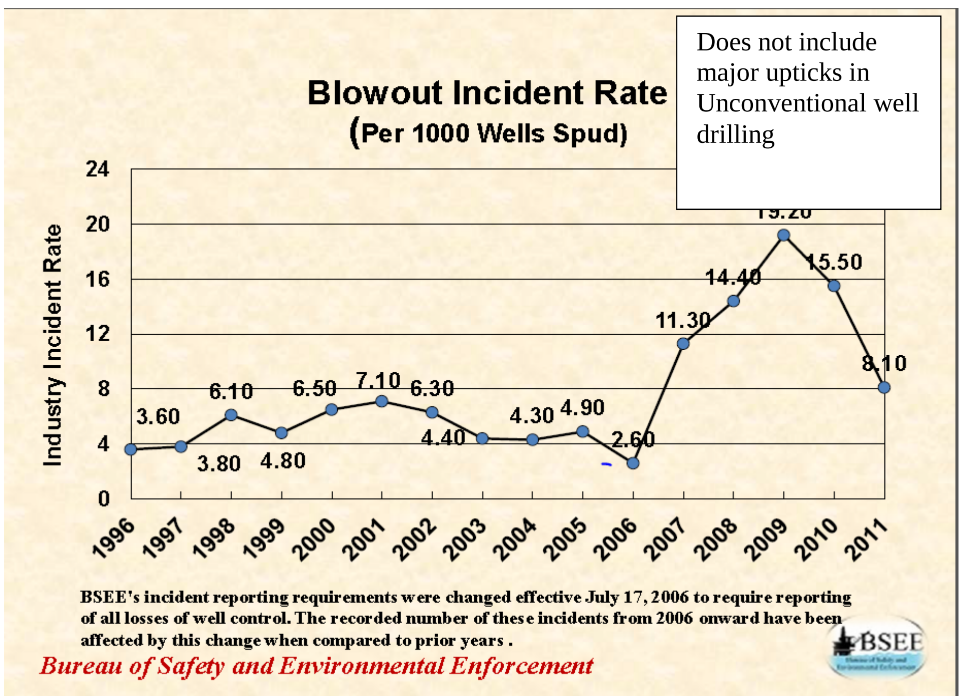


Figure 4: BSEE Blowout Incident Rate (Losses of Well Control)

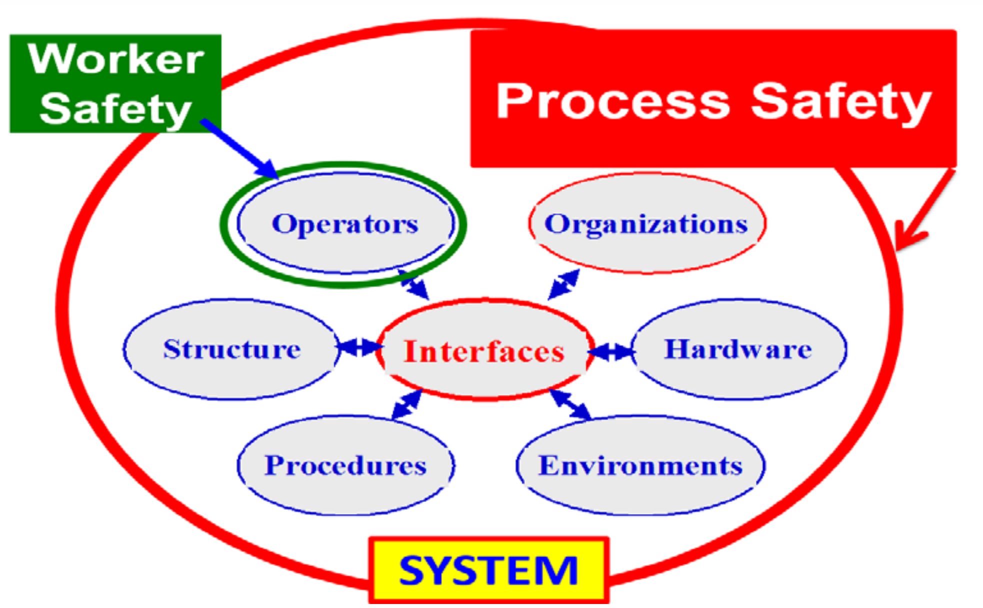
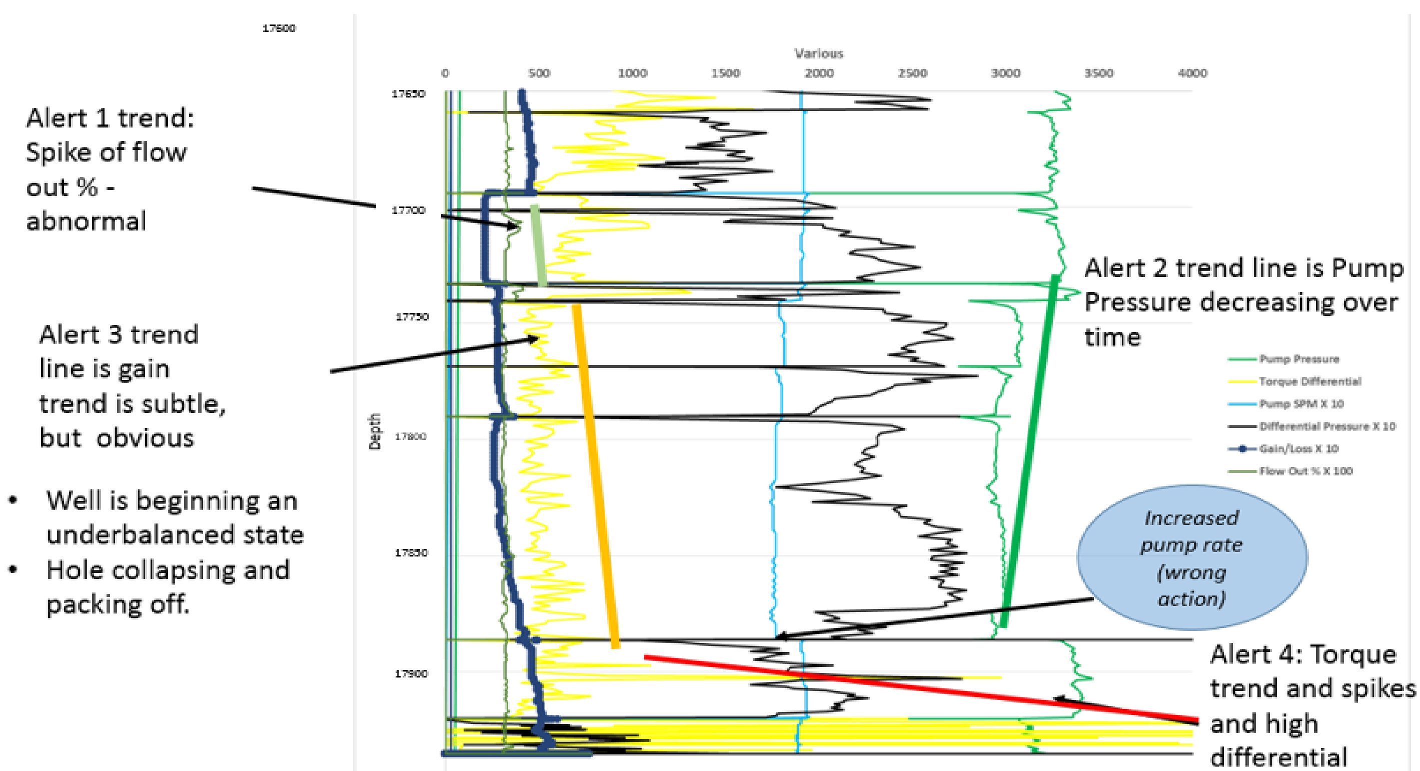


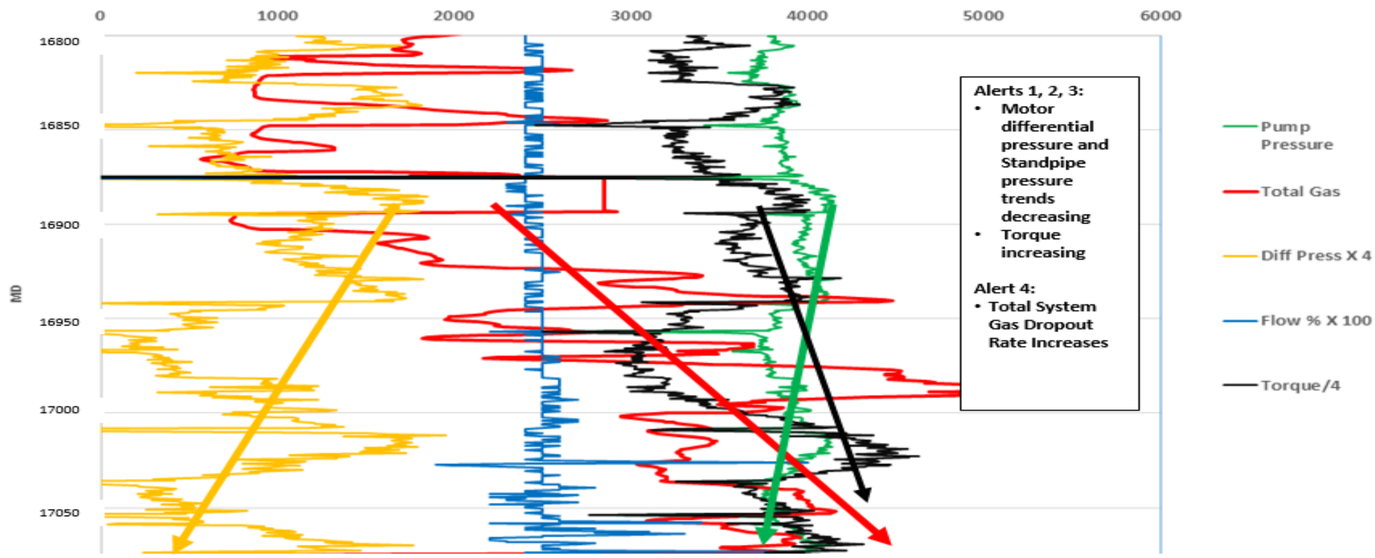
Figure 5: Worker (Personal) Safety and Process Safety[15]



A summary of progressive RTD is as follows:

1. At +/-17,750 ft., pump pressure trends began decreasing.
2. Flow out spiked and flow gains were indicated.
3. The pump rate was increased and flow correspondingly increased.
4. Torque increased.
5. Drilling continued and the wellbore ultimately collapsed.

Figure 6: Horizontal Wellbore Collapse



A summary of progressive RTD is as follows:

1. At +/-16,900 ft., differential pressure and pump pressure began decreasing.
2. Simultaneously, gas peaks on connections were increasing.
3. Time for gas to drop out on connections was also increasing with upward trend spikes on flow rate.
4. Drilling continued.
5. ***At +/-17,050 ft., the seal on the rotating control head failed with over 280 psig. Sour gas and raw condensate blew over the derrick.***
6. ***The BOP sealed before the dangerous flow stream ignited.***

Figure 7: Near Uncontrolled Sour Gas Blowout in Horizontal Well

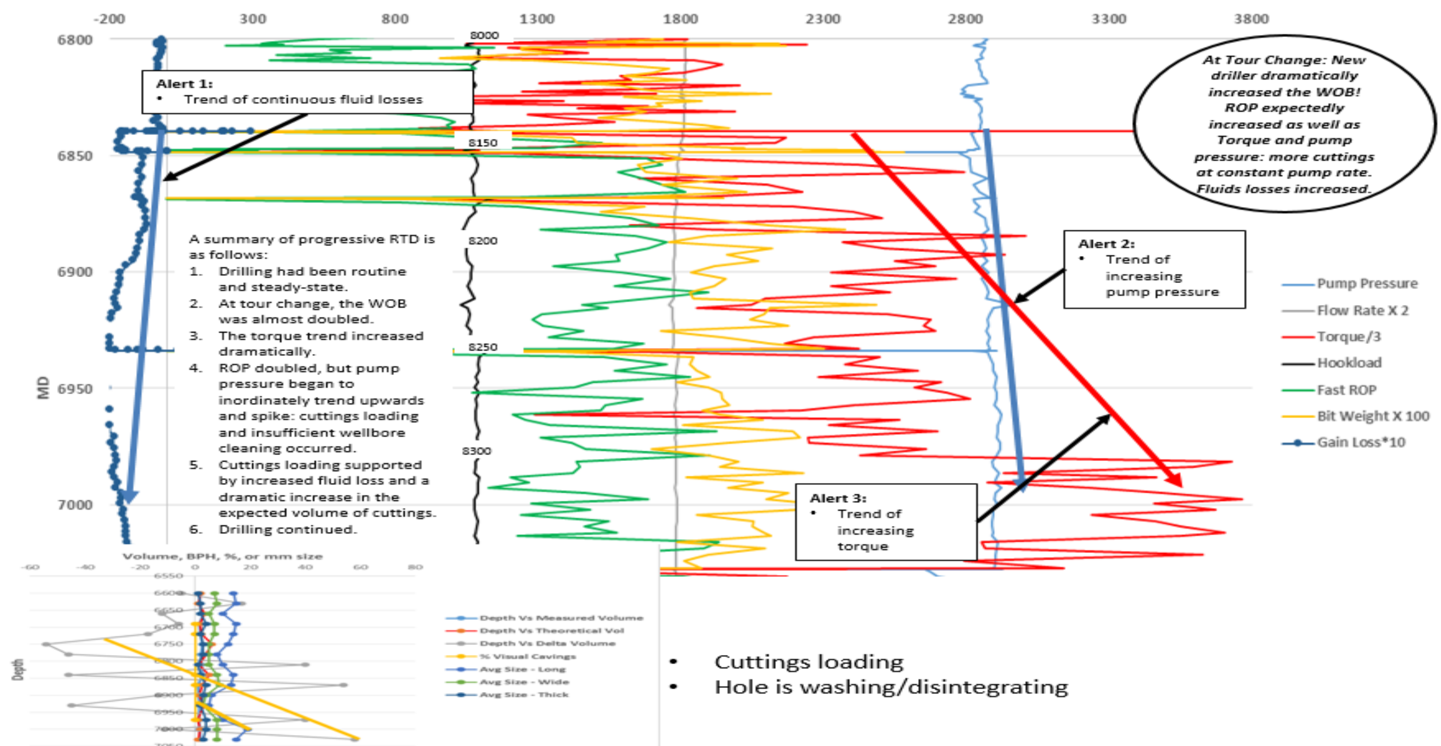
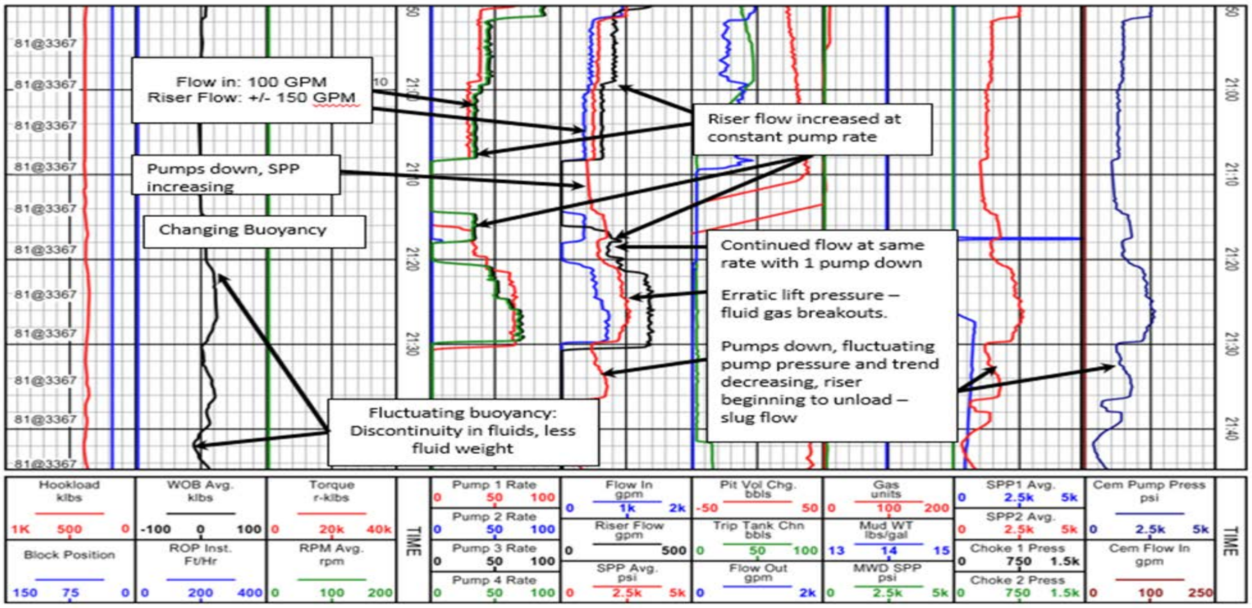


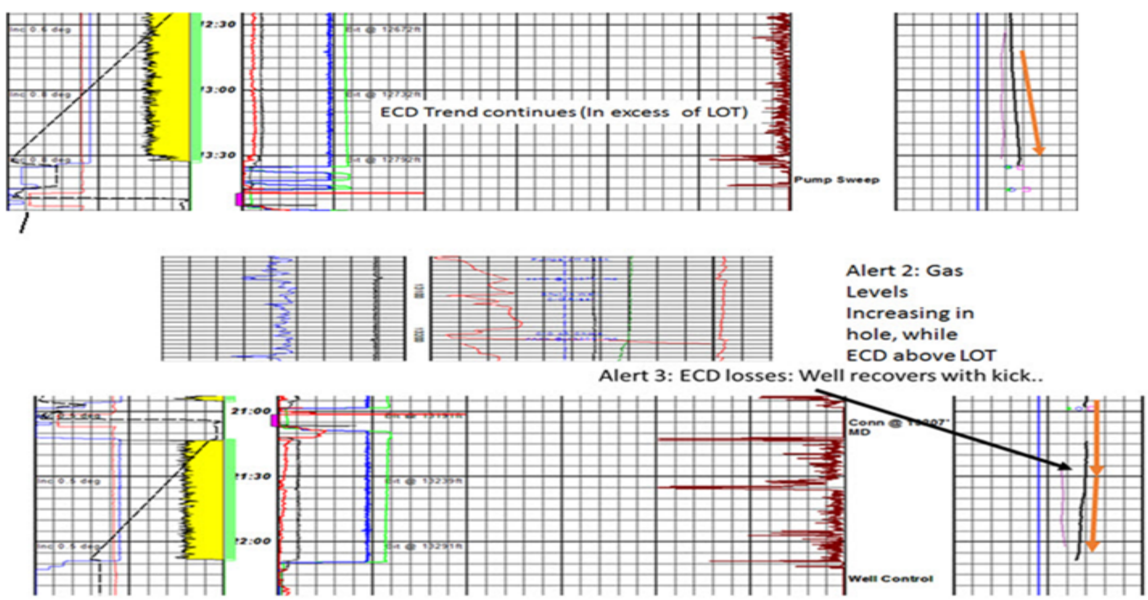
Figure 8: Cuttings Loading and Stuck Pipe



A summary of progressive RTD is as follows:

1. An inconclusive negative test on the cased wellbore had been conducted.
2. Displacement of the primary mud barrier to completion fluids was initiated.
3. The RTD discrepancies in real-time data trends clearly indicate an unstable cased wellbore long before the blowout occurred.
4. Alarms were turned off, and set "on manual".

Figure 9: Flat Time Trends in Displacement: The Macondo[19]



A summary of progressive RTD is as follows:

1. At +/- 12,200 ft., the ECD began to trend upwards after very rapid ROP: Cuttings loading
2. The operator applied a wellbore cleaning sweep and continued with an ROP too fast to clean the hole.
3. Gas levels were building in the hole. At 13,200 ft., the ECD began to reverse with fluid losses. The ECD was already above the leak-off test (LOT).
4. The wellbore was fractured and the primary barrier was compromised. The wellbore fluid column recovered with a kick.
5. With the wellbore fractured and in an at-balance situation, the ECD was too low to counter-act the pore pressure, yet too high to avoid massive fluid losses.

Figure 10: Deepwater, Fast Drilling, High ECD, Fracture Well Induced Kick.

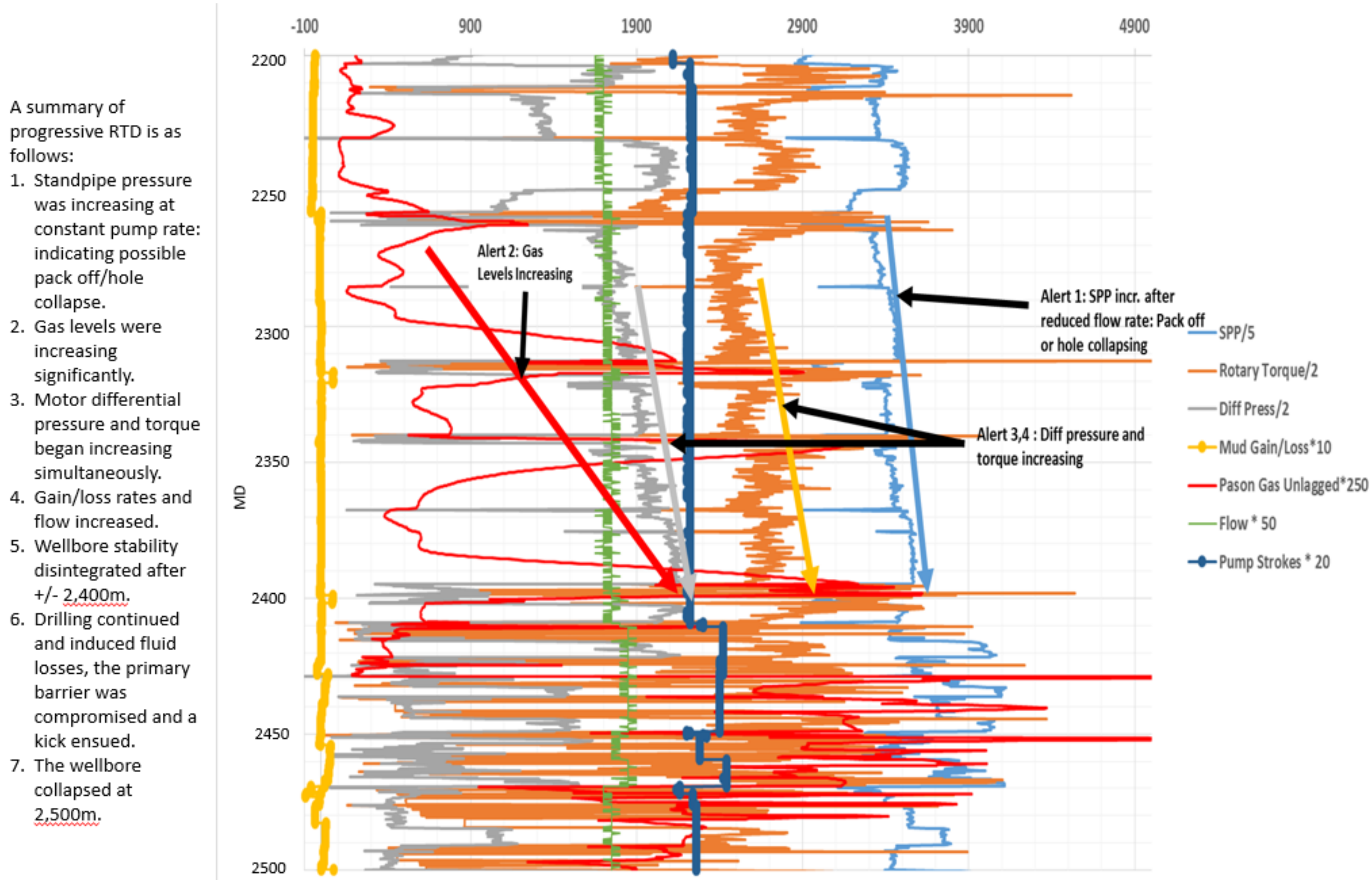


Figure 11: An Underbalanced, Collapsed Wellbore

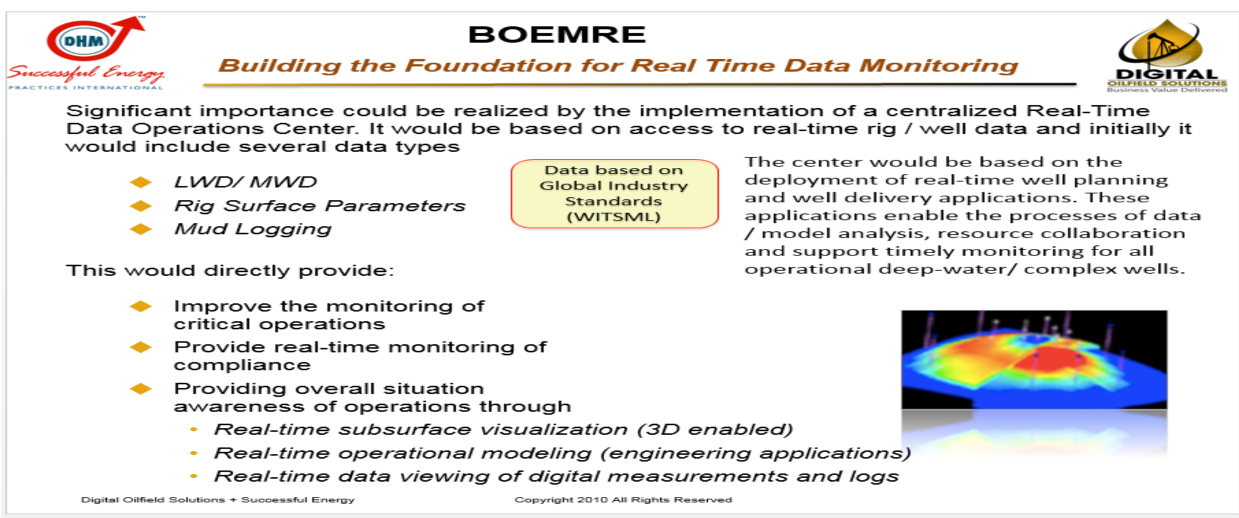


Figure 12: High-level BSEE Recommendations[20]

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[15] DR. Robert Bea, IBID

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[17] Created by David M. Pritchard to depict the governing force balances of the Physics of the Wellbore.

[18] J. Ford Brett, P.E. BOEMRE Director Bromwich Hosted Panel Session, Pensacola, FL, August 11, 2010.

[19] Macondo Real Time Data while displacing the primary barrier.

[20] Courtesy of Digital Oilfield Solutions and Successful Energy Practices LLC, July 2011. Presentation to BOEMRE, successor of MMS and predecessor of BSEE.