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A Comprehensive Review of Smart/Intelligent Oilfield Technologies and Applications in the Oil and Gas Industry

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Abstract

Smart field technologies offer outstanding capabilities that increase the efficiency of the oil and gas fields by means of saving time and energy as far as the technologies employed and workforce concerned given that the technology applied is economic for the field of concern. Despite significant acceptance of smart field concept in the industry, there is still ambiguity not only on the incremental benefits but also the criteria and conditions of applicability technical and economic-wise. This study outlines the past, present and the dynamics of the smart oilfield concept, the techniques and methods it bears and employs, technical challenges in the application while addressing the concerns of the oil and gas industry professionals on the use of such technologies in a comprehensive way.

History of smart/intelligent oilfield development, types of technologies used currently in it and those imbibed from other industries are comprehensively reviewed in this paper. In addition, this review takes into account the robustness, applicability and incremental benefits these technologie bring to different types of oilfields under current economic conditions. Real field applications are illustrated with applications in different parts of the world with challenges, advantages and drawbacks discussed and summarized that lead to conclusions on the criteria of application of smart field technologies in an individual field.

Intelligent or Smart field concept has proven itself as a promising area and found vast amount of application in oil and gas fields throughout the world. The key in smart oilfield applications is the suitability of an individual case for such technology in terms of technical and economic aspects. This study outlines the key criteria in the success of smart oilfield applications in a given field that will serve for the future decisions as a comprehensive and collective review of all the aspects of the employed techniques and their usability in specific cases.

Even though there are publications on certain examples of smart oilfield technologies, a comprehensive review that not only outlines all the key elements in one study but also deducts lessons from the real field applications that will shed light on the utilization of the methods in the future applications has been missing, this study will fill this gap.

Introduction

Most of oil fields are now mature and produce more water than oil due to water breakthrough, coning, channeling or water front arrival. This makes it difficult to economically extract hydrocarbon from the formation. Furthermore, since the oil price is not stable yet, relatively expensive technology or equipment is not interesting at all for any oil and gas company.

The obvious solution to save production performance is to increase cumulative recovery by an efficient and smart technology, for e.g., intelligent well completion by using either Inflow Control Devices (ICD) or Inflow Control Valves (ICV) as well as downhole sensor apparatus.

Improved control in large oilfields requires quick decision making while accounting for continual challenges. The intelligent oilfield can enable this by constructing a robust technology system in the oilfield by digitalizing instrumentation networks and establishing network-based information communication to optimize production activities. This computer technology will conduct a comprehensive analysis of oilfield operations. Validity of sensor information and completeness of data will determine the efficiency and accuracy of this technology.

Data mining (Big Data & Knowledge Data Base Discovery) techniques have proven to be economically profitable for oilfield control, especially in the most challenging operations (ex. drilling, extraction, modeling). Business leaders in oil and gas envision an evolved method of running their business wherein the entire operation, data and insights from data are available effortlessly and integrated seamlessly for improved decision making. However, the challenge to attain this vision in the past has been the complexity of systems, inconsistent data and high cost of required technology.

New approaches are needed to achieve this vision economically, so that oilfield business undergoes the required digital transformation. It would enable the creation of an integrated system where data and documents from diverse oilfield operations are structured, easily accessible and delivered in an intuitive manner via an interface to allow for improved sophistication in these operations. The following are few of the several barriers within oil field operations for achieving the aforementioned vision,

- Multiple types of applications arrayed across both production operations as well as business enterprise levels to manage, record and simulate operational performance.
- The applications have their own unique referral and data model, creating a lag time before data is available for comprehensive analysis.
- Information coding process and its context to instrument apparatus not transported in real time, and thus, creating an increased dependence on engineering interpretation. Processes are embedded within applications, equipment and employees.
- Not all transaction process, such as workflows, locations and events are seized in the context of instrument configurations or production related incidents.
- Operational perspective is partial; overall process analysis is less effective, sub-optimum and limited. Integration proposal for additional amenities or expanding functionality of equipment is tough, pricy as well as time consuming.
- All incident processes as well as warnings and alerts cannot be circulated and solved across the network-system to establish business processes or personnel collaboration.

Digitalization of equipment, instruments, and apparatus are creating advances in metering, measurement, automation, and control. Modeling has transformed the daily routine, for instance; decisions are made after getting better information, and, as a result, producing better recoveries in more-complex environments. All activities related to discovering model irregularities, uncertainties and improving forecasts and possibility assessments will be handled by artificial intelligence behind the scenes.

Gathering data from sensors and then transforming it into valuable information to both control rooms and smart devices is the main function of intelligent oilfield technologies. Considering the recent advancement in digital technologies, the oil and gas industry should utilize more-reliable, resilient and effective sensors. These surface or downhole sensors meaningfully increase the amount of received data, number of nodes for the same parameters, and the number of variables measured.

A valuable technique "data validation and reconciliation", as part of general industrial process can be used to deal with the massive amounts of data. Furthermore, intelligent technologies connect two different domains: the real data and desired outcomes of the modeling system.

Goals of intelligent technology in oilfields usually are cited as increasing production, reducing capital and operating expenditures, improving total recovery, and improving safety and environmental performance. These are the same goals that have been in existence in oil and gas industry for many years.

Parameters of Intelligent Oilfield Technologies

Digital Information

In the intelligent oilfield, workers and engineers are have access to all data related to their operations via an intuitive and interactive interface that enables them to instantly access key insights about their assets, from equipment sensors and documents related to their operations. This improves their decision-making ability for most operational challenges. For complex problems outside of their scope of expertise, they are now able to effortlessly collaborate with experts to identify solutions. As a result of quick and improved decision making, operational costs significantly reduce while production increase.

Management

Leadership can unlock value by streamlining operations and improving efficiency of supply chains and not just equipments. For large multi-national oil companies with assets across multiple geographies, the intelligent oilfield enables optimization across field sites, supports both inter-site and intra-site regulatory compliance, and empowers rigorous engineering performance as well as management decisions. The benefits are summarized below,

- Real-time integrated visibility: Access to all data, measurements and insights across multiple functions of an enterprise.
- Sophisticated alerts and event management: Integrated visibility enables the application of complex predictive models and business rules in the form of alerts and control for different pieces of an oilfield business unit.
- Improved process optimization: Complex KPI's and performance metrics can be calculated in realtime to enable better reporting, operational planning and decision making.

Intelligent Wells

Intelligent well completion (IWC) comprises an amalgamation of barrier per zone or per interval perforation, including expandable packers as well as sealing instruments, ICDs, ICVs and downhole radars. The current application of intelligent wells is coupled with downhole fiber optical sensors and hydraulic controlled systems. Software systems are installed on the surface as well as in critical electronic devices, permitting easy entry for preservation and healing operations.

Downhole sensors, ICDs and ICVs deliver various abilities for fluid flow control by operating manifold open and close flow points, in single or multilateral wells. ICDs consist of 2 types of binary controls for opening and closing as well as variable control for intermittent and stage-wise. Both ICDs and ICVs are critical equipments within IWC systems.

Progress & Integration of Smart/Intelligent Oilfield Technologies, Devices, and Tools

In fact, the digital revolution in oilfields had started in the 1960s due to the continuously rising needs of the industry. Thus, digital automation has inevitably gained significant importance in each phase of upstream operations. From this point of view, increasing technological advances realized particularly in last decade have resulted in the efficient usage of "smart/intelligent oilfield" concept from reservoir management till the end consumer(s) to improve economical feasibility of operations.

As mentioned before, technological improvements exponentially booming in the digital world in recent years are to cover a variety of the devices and tools developed in relation to not only the reservoir engineering aspects but also the other sides of oilfield systems that petroleum companies must understand and integrate into their systems successfully (Fig. 1).

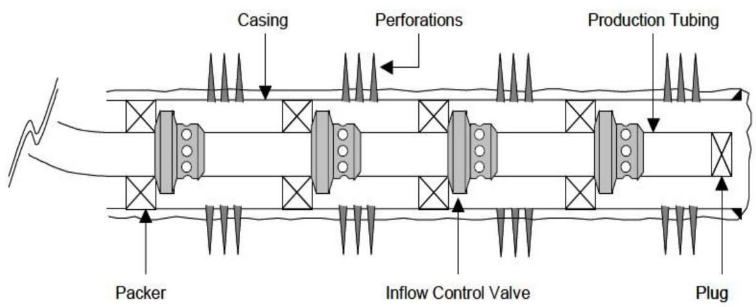

Figure 1—An Intelligent well completion system

Digital oilfields can provide significant opportunities to improve the existing condition of oilfield assets in the context of reservoir engineering and production performance as well as drilling operations. Especially in recent years, since the "digital oilfield" concept has acquired multiple definitions, some new terms have come into the fore such as smart fields, intelligent fields, i-Field, e-Field, RTO, etc. Digital oilfields cover various cyclic processes like digital data acquisition, including more accurate measurements and validation of data, storage and its protection. This is coupled with continuous optimization of processes that contain data and information, by using dynamic decision-making mechanisms, for e.g., through remotely controlled devices. Among the digital oilfield projects implemented in the past, it has been observed that reservoir surveillance and monitoring for optimization production improvement was the focus of most of those operations.

Workflows, Technological Components, and Criteria for Successful Implementations of Smart/Intelligent Oilfields

Successful implementation of a digital oilfield project is based on the appropriate combination of organization, processes, and technology in coordination with management systems (Fig. 2). Therefore, economically feasible and/or technically successful development of this type of system can be achieved better by good collaboration with all the elements of a management system.

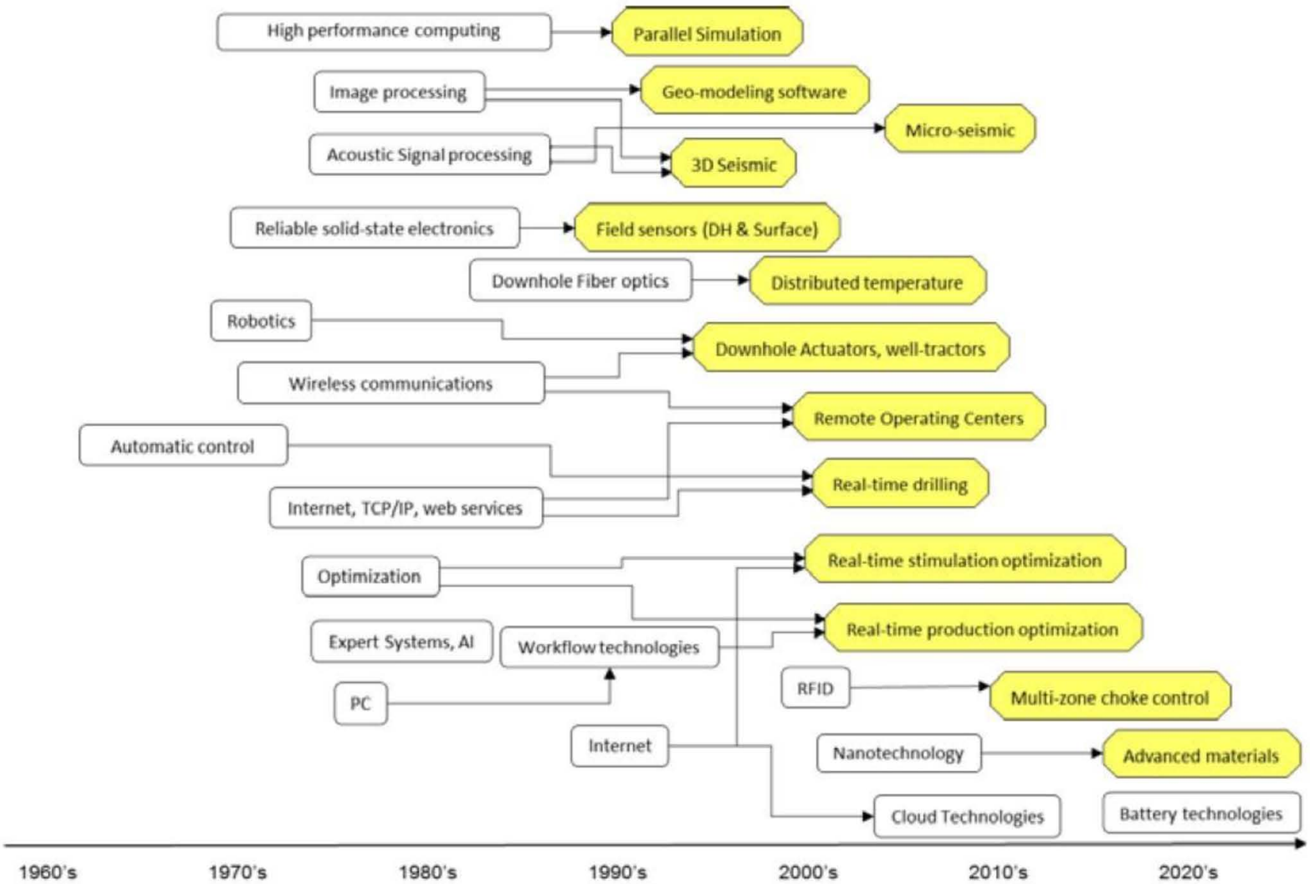

Figure 2—The progress of digital oilfield technologies in years

Appropriate project management procedure is the main criterion to ensure a successful project (Fig. 3). To integrate complicated systems, three basic approaches can be made use of as follows,

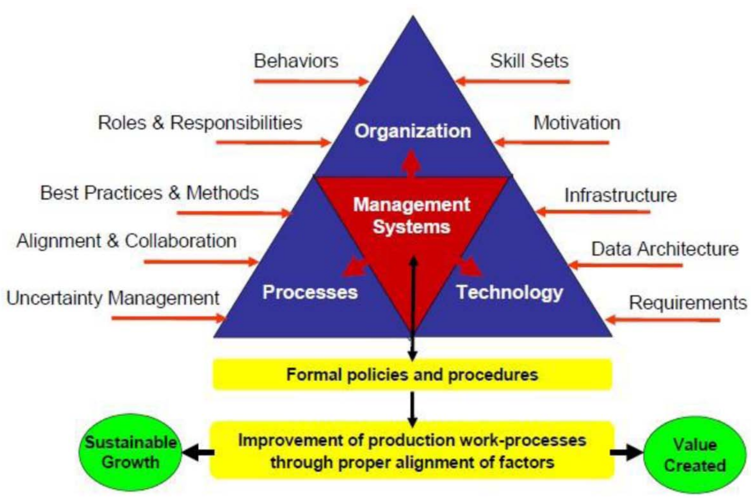

Figure 3—Context and structure of a smart/intelligent oilfield that covers the organization, processes, and technologies connected with formal policies and procedures

- Support both the management and technical teams, where some plans should be made to integrate built-in and external information.

- Allowance of sufficient duration for evaluation of available resources and construction of business scenarios with the system users.
- Taking up a conceptual design which brings the engineer into focus.

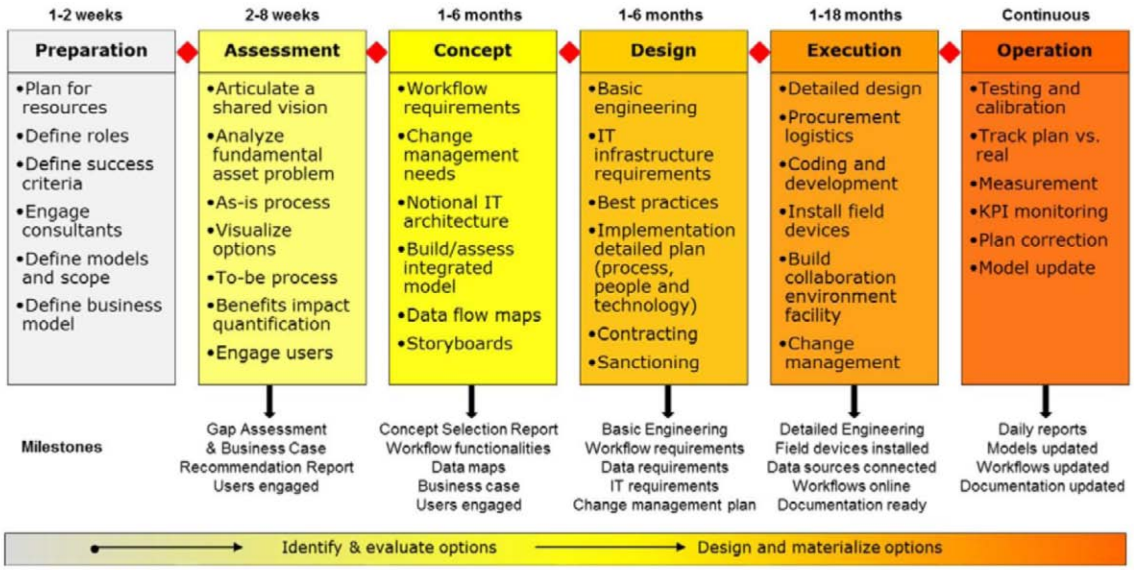

Figure 4—Implementation phased approach for successful smart/intelligent oilfield project

According to a study based on a screening technique for the implementation of smart/intelligent oilfields in terms of reservoir engineering, four main criteria - economics, environment, geography, and technical factors - have been defined for these systems to be economically feasible and/or technically successful. Economics and technical factors are the most significant. Economical factors can be divided into three primary parts as CAPEX, OPEX, and revenue having the highest weight among them. Technical factors consist of numerous reservoir properties, well completion information etc. The technological necessities for smart/intelligent oilfields can be divided into four main compartments containing information technology infrastructure, field instrumentation and control, workflow automation, and multidisciplinary collaboration (Fig. 5). The architectural structure of a digital oilfield IT depends on the description regarding two principal layers (Fig. 6). The first one is data and application integration layer that provides data and information transfer among the records of the venture system such as completions, seismic, well tests, etc., and workflows such as well test validation and model update, reservoir pressure update, and energy management purposes. The second one is related to information connecting the earlier mentioned workflows and visualization applications that are used for continuous asset surveillance (well performance, event detection, etc.), optimized production settings and improved perfromance forecasts (well integrity, capacity constraints, health, safety, and environment, etc.).

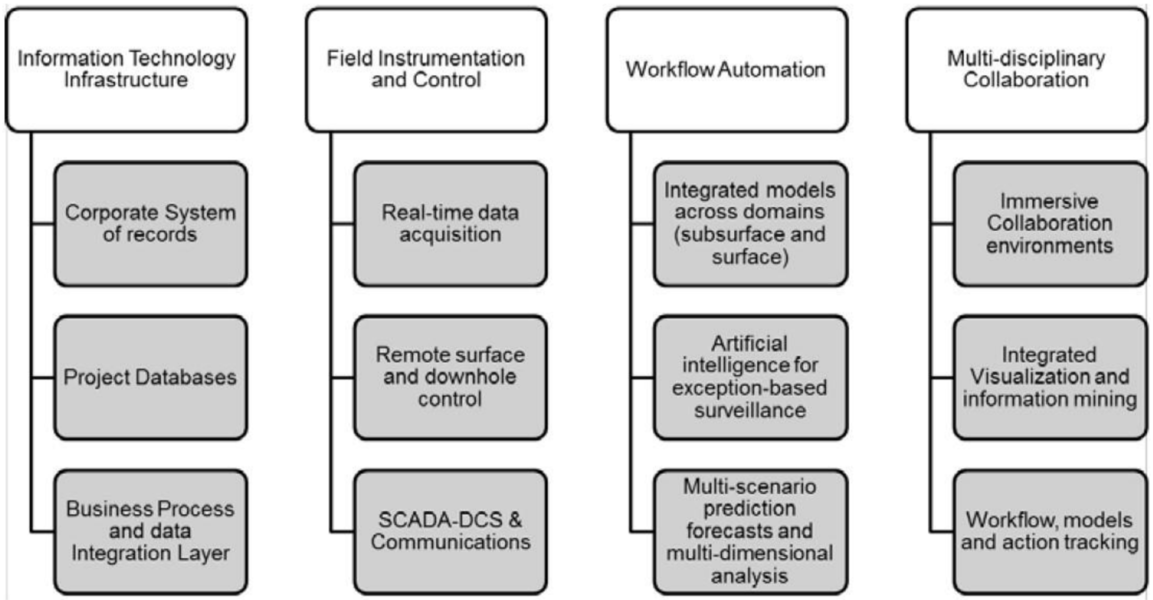

Figure 5—Technological components of smart/intelligent oilfields

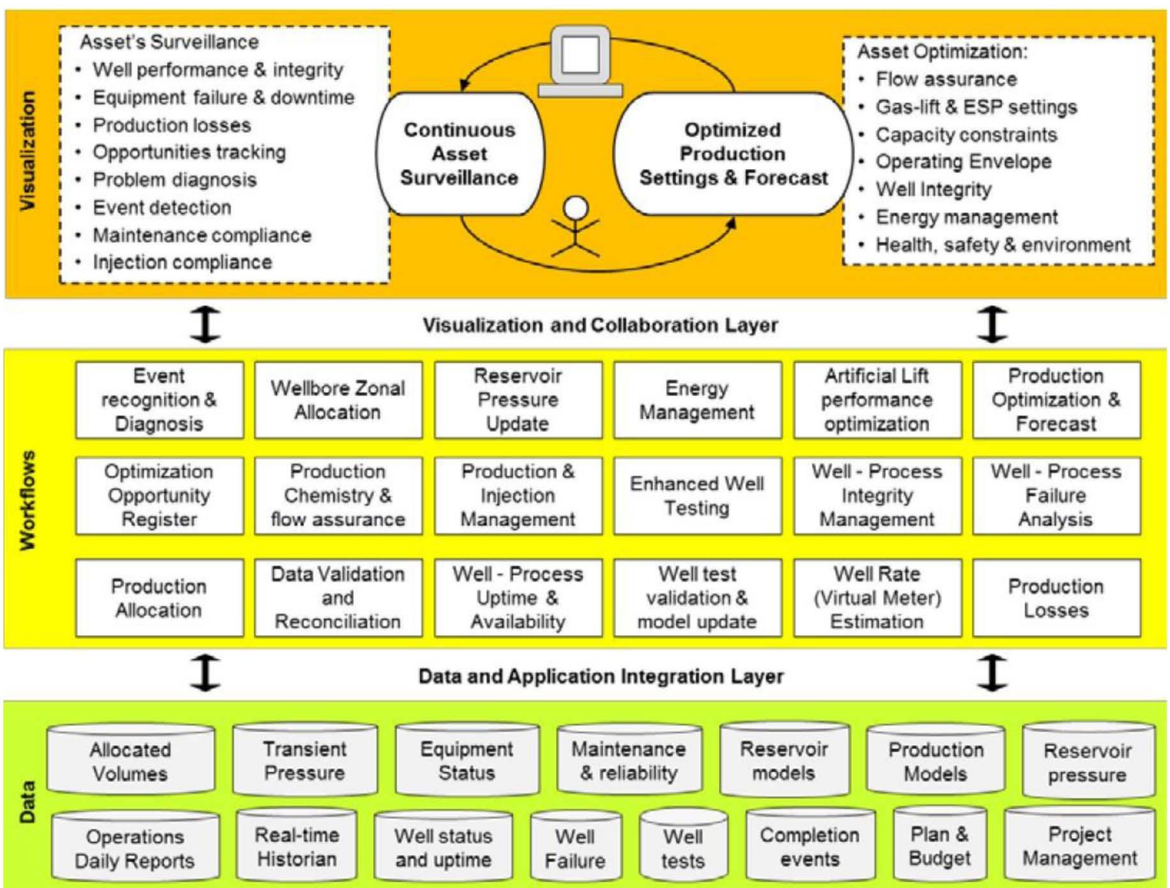

Figure 6—The architectural structure of smart/intelligent oilfield IT

Smart Field Collaboration Centers and Real-World Examples

Various perspectives in terms of the reservoir engineering aspects are available about the frameworks implemented for information transfer between production applications. For example, the Integrated Operation for the High North (IOHN) was improved as a remarkable project by the Norway Scientific

Council and Statoil with some services companies. It is possible to increase the examples comprising the i-Field of Chevron, the Smart Fields of Shell, the Field of the Future of BP, Digital Program of ExxonMobil, Intelligent Field Program of Saudi Aramco, and GeDig of Petrobras. For instance, the i- Field of Chevron that means the "integrated field" contains a point of view related to operational transformation that enforces enhanced and optimized applications having joint aspects expressed as "managing by exception focusing on the greatest value", "improving collaboration across distance and functions", "standardizing and centralizing analysis and decision-making", "using relevant-time data in decision-making", and finally "reducing ad-hoc trips to fields".

Asset Management & Digital Technology Implementation Areas in Smart/Intelligent Oilfields

Asset management is very important for smart/intelligent oilfields in terms of reservoir engineering aspects. We can divide it into two main parts integrated asset management (IAM) that involves in the applications regarding the whole asset management and real-time production optimization (RTPO) that contains the applications related to wells to optimize the productivity (Fig. 7). In IAM, applications such as advanced geology and integrated interpretation platforms, high performance computing center for multi-scenario analysis and multi-million cells reservoir simulation, automated reservoir history match, real-time down-hole pressure and rate analysis, real-time reservoir surveillance practices using seismic-based, electro-magnetics, tracers, streamline simulation, and data-driven, smart waterflooding, integrated forecasting, integrated planning and scheduling, automated asset portfolio management, and surrogate and proxy modeling of subsurface are implemented. By contrast in RTPO, the applications such as automated workflows for well test validation, well model update, plant update, real-time key performance indicator (KPI) calculations, real-time integrated production optimization, virtual metering systems (VMSs) including multiphase flow rates, soft sensors, and zonal allocation, smart well monitoring and control, smart diagnosis and by exception-base surveillance, expert alarming, predictive advisory short-term forecast, artificial lift diagnosis and optimization, immerse collaboration environments, remote operating centers, operations dynamic simulator, advanced process control may be implemented. Actually not only should the technological advances be involved in smart/intelligent oilfields, but also independent workflows should be taken into consideration and developed specifically on the area to be projected to maximize the efficiency that can be obtained from the field.

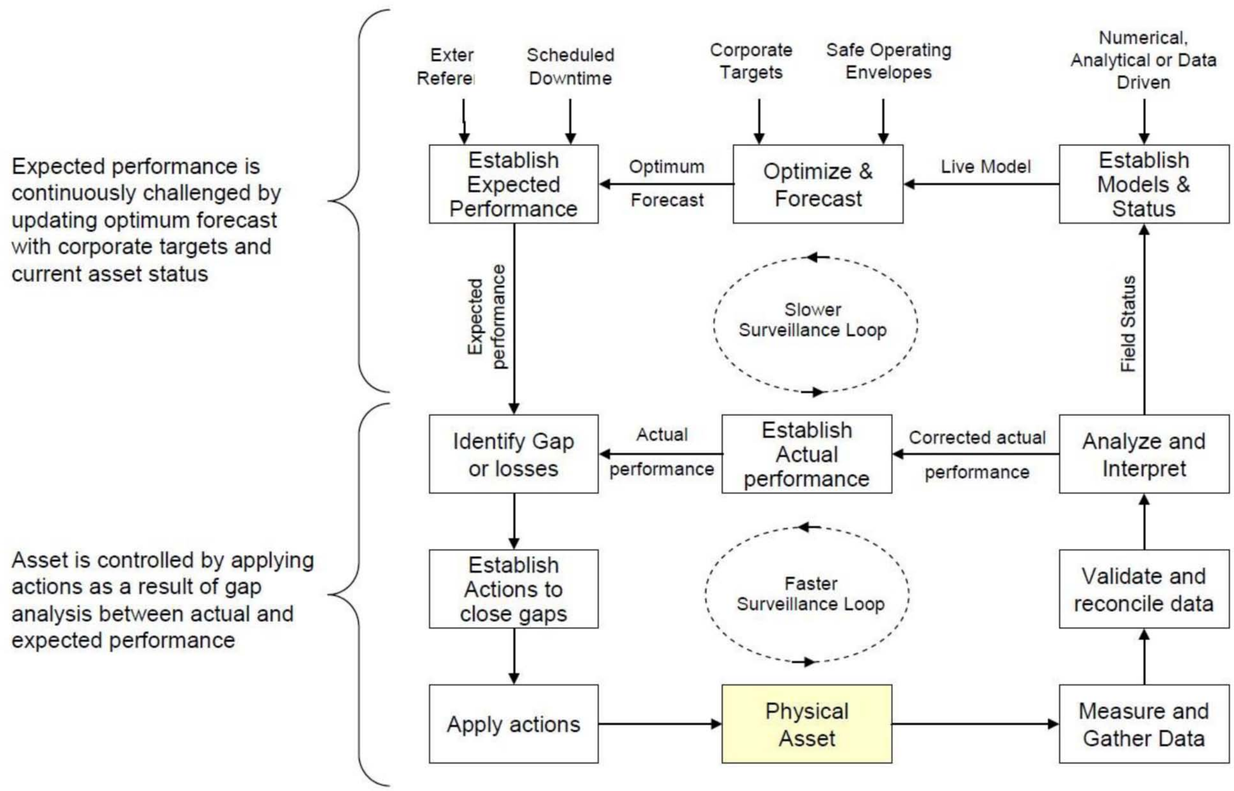

Figure 7—Basic workflow for RTPO

Success Stories, Workflows, Technologies, and Benefits from the Real Smart/Intelligent Oilfield Projects (Onshore/Offshore) from the World

There are numerous real field applications and success stories also inserting these recent technologies into those projects in reservoir engineering aspects of smart/intelligent oilfields around the world. In Barracuda and Caratinga, deep offshore fields in Campos Basin, Brazil, the smart oilfield project titled "Barracuda & Caratinga Real-Time Operations Monitoring" was started by Petrobras in 2005, with Halliburton as the technology provider. Project scope included production monitoring and optimization of 34 production wells on a waterflood offshore field characterized by medium-light oil. In this application, the workflows which are daily operations report, well test validation, asset availability, KPIs, virtual multiphase metering, real-time simulation, and integrated production optimization have been implemented. According to the primary technologies such as workflow management and service-oriented architecture utilized in the applications, workflows were implemented to yield real-time key performance indicators to enhance production monitoring and optimization as the main benefits gained from the project.

In 2011, in an onshore field in North Alberta, Canada, Shell began a project titled "Best Practices and Lessons Learned After 10 Years of Digital Oilfield Implementations". It was conducted to understand the efficacy of their smart oilfield w.r.t full field monitoring and optimization of 120 production wells characterized by heavy oil with 8 API. In this project, the workflows, daily operations report, well test validation, asset availability, KPIs, virtual multiphase metering, and real-time production optimization have been implemented. With the primary technologies, VMS for all wells for continuous, dynamic, exception-based surveillance and optimization within real-time constraints and workflow management used, the field has sustained 8% production gain as the main benefit.

In 2011, in the Malaysian part of the South China Sea, Shell Sarawak Berhad started a project in multiple-integrated gas fields called "Real-Time Optimization of an Integrated Gas Production System Implementing Models for Real-Time Monitoring and Optimization of Wells and Facilities". Project scope included RTO of wells and facilities on a gas production network spanning more than 100 wells, 40 platforms across several different Production Sharing Contracts (PSCs). It included more than a 1000 variables, mutually dependent objectives and constraints. The workflows developed, manage and continuously optimize complex, supervisory control for gas production assets, daily production targets, actual production and condensate/gas deferments. The outcome of this project was that through the use of primary technologies VMS for continuous, dynamic, exception-based surveillance and optimization condensate production increased by 5%.

In 2009, in a Western Siberian field of Russia, Salym Petroleum partnered with Shell as the technology provider to start "Well and Reservoir Management Project at Salym Petroleum Development" project. Project scope included artificial lift (with ESPs) surveillance and optimization by secondary recovery with water injection. In this project, the workflows for supervisory ESP well control and water injection surveillance have been implemented. With the primary technologies VMS, IFM, and EOR, major benefits were reduced ESP trips (increased ESP MTBF from 605 to 650 days with projected OPEX costs saving of $2.5 million in 2010), 33% increase in operator productivity, and reduction in unscheduled deferments.

In 2008, Shell North Sea and West Africa initiated a the "Improving Allocation and Hydrocarbon Accounting Accuracy and Automating KPIs" project for real-time allocation and automated daily reporting of more than 50 wells represented by two gas lifted fields containing medium-light oil. The workflows, daily operations report, KPIs, virtual multiphase metering, and continuous surface and zonal allocation have been implemented. Increases in allocation factor accuracy have been obtained from the fields with the VMS technology.

In 2002, multiple Shell Operating Units participated in a project titled "Business Value from Intelligent Fields". Project scope included reservoir to point-of-sale containing different types of hydrocarbons. Workflows for remote control, reservoir surveillance, RTO, collaborative working environment (CWE), rotating equipment monitoring have been implemented through this project. Major technologies included smart wells, 4-D seismic, VMS, integrated production model, and CWE. The overall quantified benefits were $5 billion in realized value until 2009. The main contributor was a production increase of 70000 bbl/day and total CAPEX reduction of approximately $800 million.

Technological Challenges Regarding Implementations in Smart/Intelligent Oilfields

There are some technological challenges with reservoir engineering applications in digital oilfields - Data quality, model update, digital oilfield as a supporting mechanism, areas for joint collaboration, digital oilfield standards, the reliability of systems, data security and ownership, and smart workflows. Data quality could be problematic particularly for RTP optimization and surveillance. This problem can be diminished by data validation based on mass balance reconciliation. Model update is another complex issue faced in these fields as accuracte adaptation is required while developing the model from the older version to the newer one. Such problems can be handled with the sound integration of data and implementation. Digital oilfield will be ideal a supporting and complementary implementation, and not an independent and alternative application to the available systems and conventions, which by combining information gets the maximum efficiency from both measurement devices and tools. This process will also contain a transition period and require the use of existing systems for a certain period of time. Areas for joint collaboration containing new technologies and workflows should cover the interconnections between operating companies and technology providers regarding internal activities and collaborative systems. Digital oilfield standards depend on the continuous integration processes of data, its implementation and improvement along with other common standards used in industry. Data security and ownership is another problem caused by multiple users' access to the information systems. Safe and secure usage of these systems creates another challenging issue.

Recent Advances in Smart/Intelligent Oilfield Technologies

It is possible to summarize the advances and future trends associated with smart/intelligent oilfields in recent years with three main items.

- *Industrial Internet of Things (IIoT):* This concept is to contain the technological developments regarding the advanced sensors and built-in artificial intelligence implementations.
- *Big Data and Analytics*: This is another popular and hot topic based on communications between human and machine and supporting systems for decision-making.
- *Advanced Cyber-Physical Systems*: These types of systems are related to the cyber-physical security technologies and processes, robotics, automation, and improvements in controls of process.

Usefulness of Intelligent Technologies in the Oilfield

The intelligent well technology has gained a recognition in giving huge advantages in recovery effort, especially Enhanced Oil Recovery (EOR) processes as well as in unconventional oil fields. The target of intelligent technology is to have automation wherever possible in the production process. It is allowing to improve the value of an asset.

Another benefit of intelligent well system is a cleaning up function. Cleanup operations can alter formation properties due to invasion of drilling and completion fluid filtrate. Technically, the ICVs within each length of production tubing can equalise inflow potential and pressure drawdown along the installed length.

Technical optimization as well as economic evaluation shows that ICVs and ICDs have more advantages than conventional, open-hole completions for a long, horizontal well in term of the cleanup efficiency, since the filtrate saturation in each horizontal section exhibits relative overall decrease.

Oil and gas companies invest an exorbitant amount of money into exploration for new fields and enhanced oil recovery operations. Additionally, oil and gas companies have an institutional way of working; a combination of different units working seperately from one another. Unfortunately, these results in lesser communication across units within the same company. New approaches are required to overcome these challenges.

Based on increasing energy demands from developed countries and reduction in proven reserves, oil companies will need to find out new ways to enhance productivity while reducing cost. Smart oil and sas field technology revolutionizes legacy systems that heretofore have been laborious, tedious and wasteful. Today, embedding industrial machinery with software and sensors is improving operational performance. These embedded sensors feed companies wireless live data streams, enabling analysts to configure dashboard monitors to graph and visualize measurements and statistics to improve decision-making and operational efficiency.

According to a research study conducted in Latin America, engineers spend most of their time looking for data related to current processes and less time on actually analyzing information or carrying out substantive responsibilities that produce technical value for the company. Clearly, the trifecta of infield measurement devices, real-time data and advanced algorithms have the potential to maximize productivity. They can reduce time wasted on chasing down and recording data, and free up engineers to spend more time on anaylzing the data.

Motto behind the technique is setting sensors where data would likely be gathered, and integrate them to prevent any damage in equipment, avoid lagged production, and perpetually preserve the reservoir. Effective usage of field equipment is an essential factor to maximize oil and gas recovery. Smart oil and gas field technology has been the primary route for the industry since over a decade to achieve this.

For example, in the middle east, more than 60 smart oil and aas fields have been integrated into one system with a national remote operations center, and diversified control and monitoring systems. The system displays alarms and reports on more than 1 million field data points. In most fields, companies use SCADA (supervisory control and data acquisition) systems to monitor wells. Data such as well operating conditions, flow rate, well head and bottom hole pressures and temperatures can be gathered.

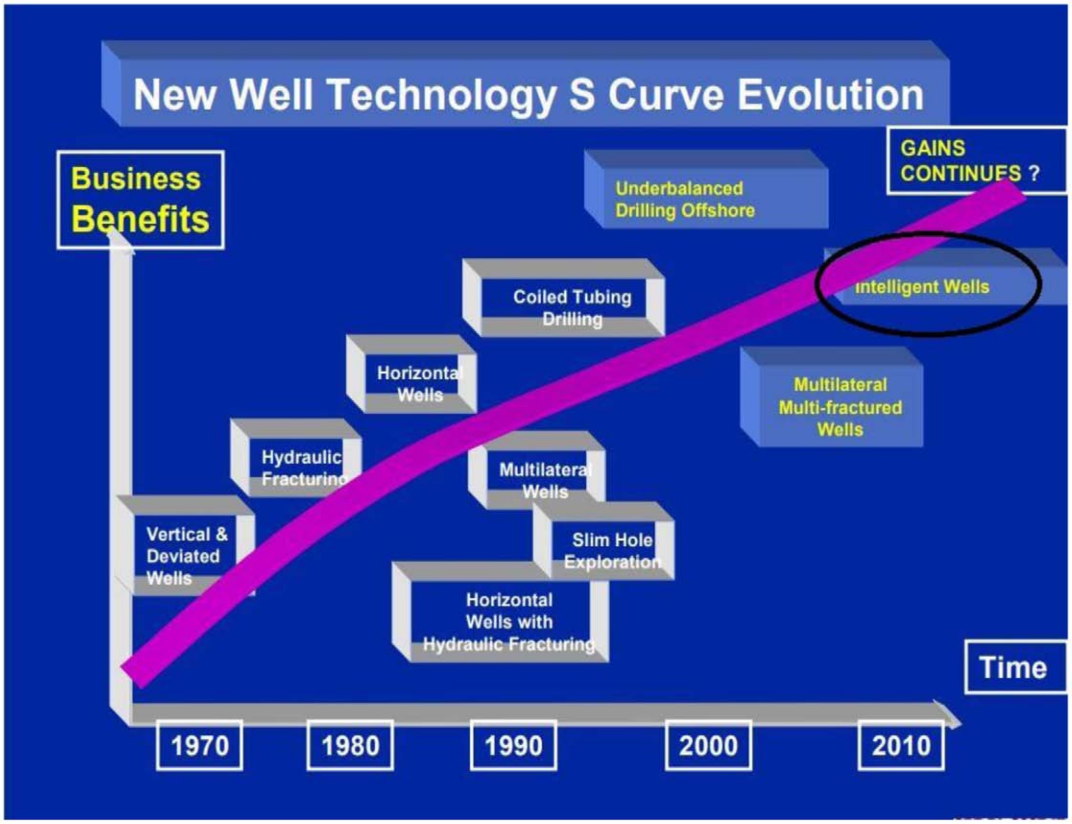

Figure 8—Evolution of New Well Tecnology

As previosly mentioned, smart oilfield technology has been implemented by various companies. Major oil and gas service companies have been working on improving programs in order to satisfy customers needs. Baker Hughes, one of the leading service company invented The InCharge and InForce Technologies, a program has the ability of data acquisition and flow management, and can monitor real time measurement. Halliburton and Shell have a joint venture company named WellDynamics for reseraching and developing smart well technology. Schlumberger's controlling and reservoir monitoring system combines reservoir monitoring and stratified flow control. Weatherford's program, the simple intelligent TM system, unites fiber sensing techonology and flow control systems to optimize the reservor inflow profile to improve recoery rate, and optimize production performance.

Qatargas, one of the world's largest gas producers and LNG exporter, has built corporate database where all the collected data are checked and loaded. The company aims to reduce man hours spent in addressing challanges in daily activites, and comprehension during irregular gas plant operation conditions such as machine trips, slow downs and shutdowns. Shell Oil Co. and Petroleum Development Oman have equipped wells with digital sensors, where real data and adjustments can be monitored from several kilometers away. The companies seek to reduce the time techinicans spend outside, where temperatures can reach up to 50 degree Celcius. Technicians also can join video conferences with specialists sitting anywhere in the world from remote locations. It's all about saving time and money.

Development of the smart oil and gas field technology has passed through many steps from dumb fields to smartfields and finally intelligent fields. The first known study about smartfield technology was started around 1994. From that time to now, studies have been crucially important on this technology in the O&G industry, and universities. Viterbi School of Engineering at University of Southern California provides grad students a master degree in Smart Oilfield Technology. University has a technology center with Chevron established in 2003, CiSoft, a center for interactive smart oifield Technologies for research and academic training.

It has been proved that, data collected from sensed materials has become important business assets, which urges decisions on where to invest or when to divest, and how to manage more efficiently.

Drilling/Facility Engineering Aspects

The drilling industry showed an impressive development that enables significant increases in the rate of data telemetry and real-time control of downhole tools in last decade. The system that consists of new technology tools that can sense downhole conditions and adapt itself to these conditions by providing step by step drilling process control is named as "Smart Drilling System" (Lurie, 2003). These systems could enable directing the operation from the surface or any remote location by utilizing a remote-guidance system. Moreover, the rapid innovations in computer science and microelectronics paved the way ofn how sensing systems could measure the parameters and describe the deviations by comparing them with the expectation and boundary inputs. Thus, the system could also perform as a self-guided system which modifies the drilling operation trajectory itself.

Well integrity and drilling technology are the main technology development areas of the drilling industry. Mainly, well integrity can be classified in two main categories; pre-production and production well integrity. Herein, we will concentrate on the pre-production wellbore integrity and new developed drilling technologies as crucial parts of the drilling process. Vital research areas of drilling processes can be classified into the following sections,

- Improved Well Construction Materials and Techniques
- Wellbore Integrity
- Technology and Tools for Remediation
- Fit- For-Purpose Drilling Tools
- HPHT Well Construction Technologies

Improved Well Construction Materials and Techniques

In drilling, it is crucial to develop smart materials that are more reliable and robust in particular sections such as, drilling fluids, lost circulation prevention materials, enhanced casings, cements, and centralizers. For instance, lost-circulation problems were prevented by using advanced chemically inert fibers instead of using conventional techniques such as limiting friction pressure, reducing slurry density or performing stage cementing operations (Abbas et al, 2003). Expandable casings are also new technology materials which have started to see widespread use (Cooper et al, 2009). The next step of development process can be counted as commercializing cement/casing systems, reinforced by polymer nanostructures that can heal itself in case of any mechanical or chemical damage (Mangadlao, 2015; Vipulanandan, 2015). Another point of motivation is to develop highly efficient and stable cementless casing systems and techniques (Fig. 9). Cement bonding is another parameter that affects the success of drilling operations. Bonding between casing and rock ensures stabilization and reduces casing failures. It is worth to point out that casing centralization is a major parameter of a successful cementing operation (King and King, 2013). Cement bonding can be enhanced by using improved techniques such as pre-treatments in the wellbore or cleaning the annulus with advanced chemicals. Drilling technologies such as ‘gun barrel' holes can be used for zonal isolation and to increase bonding efficiency of cements (Muhammad, 2009).

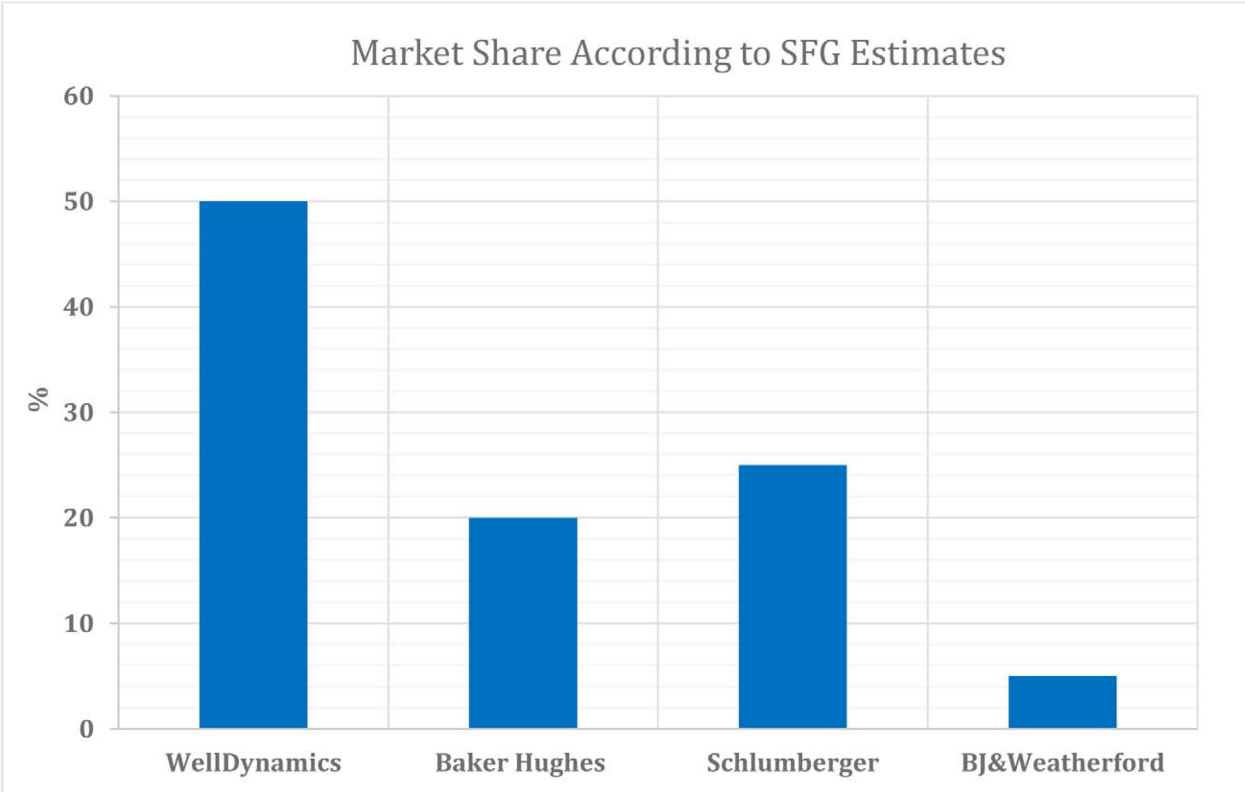

Figure 9—Smart Well Technology Market Share

Wellbore Integrity

Wellbore integrity problems can occur in both pre-production and production stages. Main pre-production problems are caving, incomplete cementing, inadequate drilling mud removal, incomplete cement placement, inadequate cement-formation bond, inadequate cement-casing bond, cement shrinkage, and contamination of cement by mud or formation fluids. Wellbore integrity problems can be a result of well leakage, which negatively impacts groundwater quality, environment, human safety and carbon storage credits. Moreover, it contains risks that depend on the reservoir and wellbore system. Therefore, it is crucial to develope completion systems which probes the downhole environment with sensors and enables continuous real-time wellbore monitoring. The sensors can provide valuable information that could prevent any failure harmful to wellbore integrity. A casing system can be modified to monitor the downhole parameters such as; casing stress, corrosive effects, hydraulic containment etc., and other parameters that effect the performance by using integrated sensors (Bourgoyne et al, 2000; Ingraffea et al, 2014). Additionally, it is possible to reach various missing data by using probes that could monitor and identify the downhole construction during drilling processes (Miller, 2011; Wigger et al, 2014). For instance, conventional cementing operations are performed by using water-cement slurries that are pumped down. It displaces the drilling fluid from casing-rock part and leaves the cement to harden. Integrity of the seal is ensured by pressure tests. If pressure test fails, then the casing must be re-cemented. In this case, smart materials that enable rapid setting and hardening of the cement as well as tools that can provide a robust pressure test will be advantageous to save rig time and ensure wellbore integrity (Davies, 2014).

Technology Tools for Remediation

Smart materials and remediation tools are used in wellbore remediation. It is possible to have some unintended breaches and notches sourced by corrosive effects on the casing surface. Corrosion could be caused by water seepage (in presence of highly saline and corrosive water) or obstructions during well casing cathodic protection (CP) program that decreases casing leaks due to external corrosions. Following the identification of wells, exposed sections are sandblasted. Ultrasonic thickness measurements are performed to determine the metal loss due to corrosion. Corrosion maps are generated by using the wellbore sections below the acceptable required wall thickness (Farooqui, 1998). Following the mapping, advanced technology remediation tools are used to perforate the sections and inject smart materials which are produced for previously described geologic regions to prevent corrosion.

"Fit-For-Purpose" Drilling Gadgets

It is expected that the upstream O&G industry will evolve to explore unconventional hydrocarbon resources in next ten years. Thousands of unconventional wells are already planned to be drilled in United States alone. Herein, drilling cost and efficiency are the driving factors that enable an efficient drilling operation. Deep water and onshore unconventional scenarios need robust and efficient tools for a better drilling performance. Enhancement of data is also another focal point that could improve the success of completing an unconventional well. Thats why the industry concentrated on the development of "Fit for Purpose" technologies, tools and methods. Some successful "fit for purpose" examples for handling an efficient drilling operation is given below.

Accuracy predictions can be classified as a fit-for-purpose concept on Mathematical basis error models (Williamson, 2000). Several fit-for-purpose solutions with Roller Technology, used to overcome the drag force challenges and torque problems in high angle wells were planned by Fraser et al. in 2003. The study concentrated on data collection on roller tool performance in different wells and the usage of Roller Technology enabled significant improvement in well engineering design and construction (Fraser, 2003).

UBD (Underbalanced Drilling) is also one of the fit-for-purpose solutions that could be applied in several cases such as mud cap drilling, reverse circulation, closed annular returns, lost circulation issues, hard rock, geothermal, Coalbed-methane and sour gas drilling and succeed to assist (Bybee, 2004).

Intelligent Drillstring Components which are capable to transmit the data with high rates also classified as fit-for-purpose tools. These tools are mainly designed to handle the tubular-makeup and racking problems, electrical-noise issues and temperature limitations (Bybee, 2005). MPD (Managed Pressure Drilling) is a relatively new, but proven method for efficient drilling in onshore wells. Adopting MPD technology to offshore environments is possible with a number of "Early adopters" that prove the technology to be fit-for-purpose. Another example is that, Stripper Rubber is an item that is fitted to enable stripping drillpipe and tool joints. It rotates with the drilling string and is a crucial tool which enables to classify the RCDs (Rotating Control Device) as fit-for-purpose (Hannegan, 2005). In 2006, Borland et al. investigated the effects of string sizes for directional wells with high-angle casing and described the fit- for-purpose sizes for drillstrings (Borland, 2006). As seen in Fig. 10, researchers also identified the fit- for-purpose BHA (Bottom Hole Assembly) designs and Bent Housing Angles for complex directional drilled wells (Studer 2007; Legarth et al., 2013). Beside the direct fit-for-purpose solutions, indirect methods could also help to select the fit-for-purpose solution instead of trial-and-error approaches. Wu et al., developed an advanced drillstring dynamics model that could define the root-cause of drilling vibration and Stick-Slip to guide engineers to find the fit-for-purpose solution (Wu et al., 2012). Logging While Drilling is also another indirect measurement tool which makes acoustic cement evaluation a fit-for- purpose technique to identify the cement bonding (Fuller, 2015). Abdelsamad et al. introduced a fit-for- purpose drilling system that enables efficient drilling in hard sandstone environments (Abdelsamad, 2018).

Figure 10—Well Completion can be ensured cementless by the Swelling-Packer Isolation system (Maddox, 2008)

HPHT Drilling Technologies

High Pressure High Temperature environments require extra designing challenges to reduce higher risks and maintain a successful drilling operation as well as, well construction. These design challenges can be thermal and pressure integrity issues such as, limited evaluation capabilities (most of wireline tools work up to 218°C, limited number of tools work in the range of 218°C - 260°C; optimum temperature of LWD/MWD operations is around 135°C and the reliability clearly decreases around 175°C; battery technologies of MWD operations work up to 205°C; temperature rise decreases the accuracy of sensors), low rate of penetration for production zone (compared to the conventional drilling environment, approximately 10% of rock could be removed per bit rotation; crystalline structures of Polycrystalline Diamond Compact (PDC) bits break down in HPHT environment; Roller-cone bits could not be used in HPHT environment, torque problems occur; system requires modified motor and turbine designs to increase the ROP), well control problems (drilling fluid losses; small operating window for drilling; mud storage problems sourced by well balooning; hydrogen sulfur and methane solubility in oil-base mud in HPHT conditions), and also fatigue resistance or the effects/limitations of external loads sourced by HPHT equipments on the drilling riser system (Shadravan, 2012).

All these challanges are the factors that negatively affect the structural integrity. Each component of the drilling system needs to be modified and ready for the harsh conditions and be resisted to the fatigue of HPHT environment. Sandman et al. introduced a new drilling riser system which could resist extreme loads occurs in HPHT conditions as well as the fatigue loads (Sandman, 2018).

In the first case, the endurance and solidity of wellhead systems in harsh conditions is crucial for both offshore and onshore operations. Typically, conventional wellhead systems have maximum 36-in (OD) conductor and 27 to 30-in. (OD) mandrel size. These sizes could not be enough to assure the success of an operation in HPHT conditions due to the high magnitudes and combinations of loads (Carpenter, 2016). Therefore, a comprehensive design with the usage of larger size wellheads that have larger conductor and mandrel for HPHT wells are required (Kaculi, 2015). Kaculi et al. developed a new mandrel/wellhead system with the size of 35-in (OD) and it doubled the static capacity, by 25% increase of overall connector weight compared with conventional wellhead (Fig. 11) (Kaculi, 2015; Carpenter, 2016). Furthermore, operating range of current wellhead designs are 15,000 psi and ~177°C (350°F); Some wellheads with 20,000 psi and ~177°C (350°F) max are being used rarely as well (Phillips, 2018). However, the target is to produce designs of wellheads that resist 25,000 psi and 30,000 psi with ~232°C (450°F) maximum pressure (Shadravan, 2012).

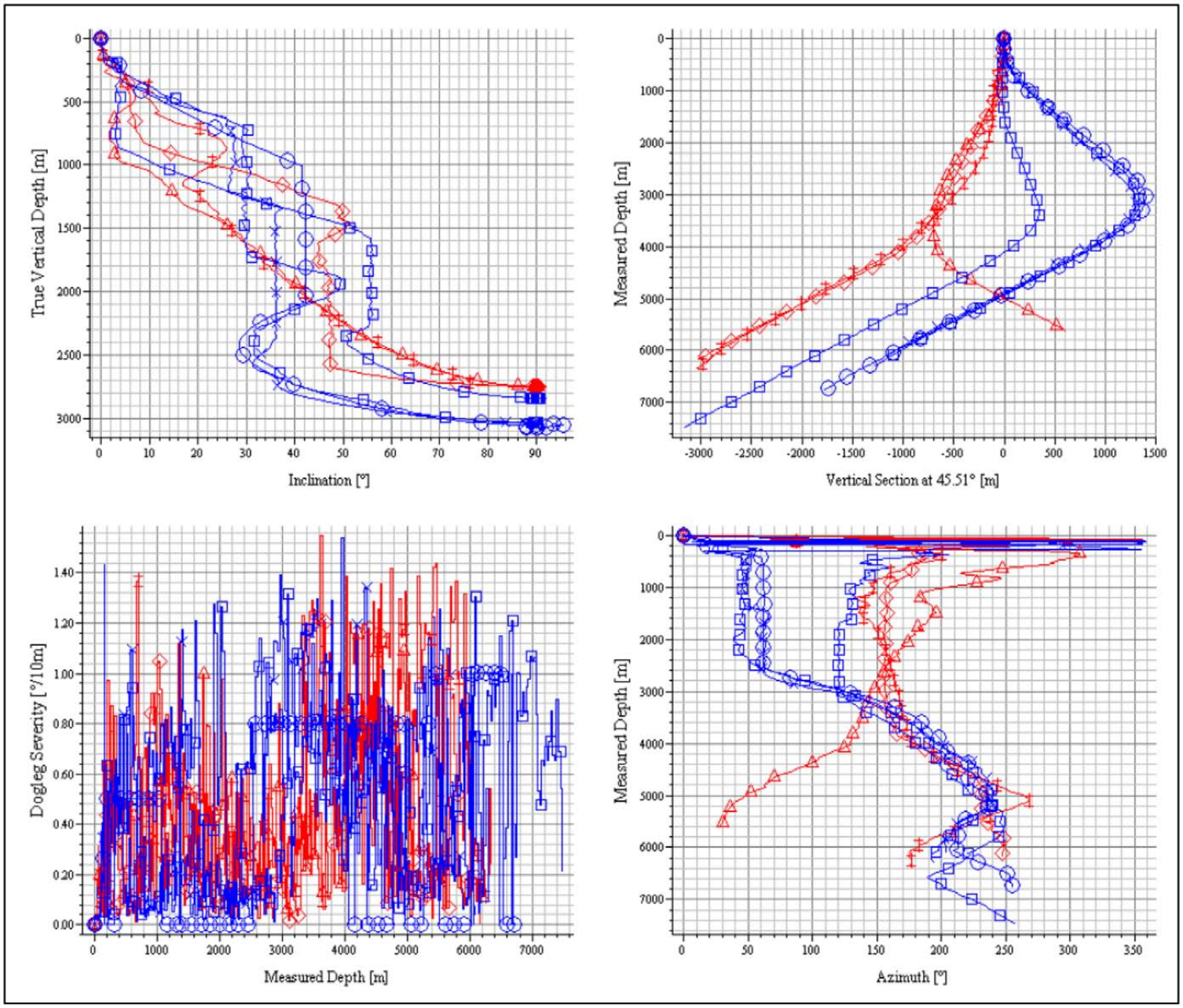

Figure 11—Effect of a "Fit-For-Purpose" Bottomhole Assembly Design (Red: Drilling with Initial BHA design, Blue: Drilling with New BHA design) (Legarth, 2013)

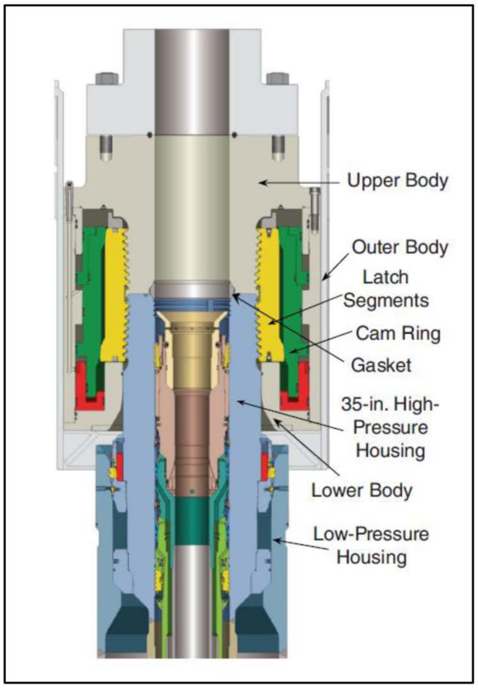

Figure 12—35-in Mandrel/Wellhead System Design (Kaculi, 2015; Carpenter, 2016)

Material properties of each component of the drilling system also needs to be identified at different pressure and temperature values for different environments (CO^2, H_2S, drilling fluids etc.). Although, some research has been performed to describe the suitable advanced materials for specific environments that includes Elemental Sulfur, CO^2, H_2S and Production Chemicals, the test is required to select the correct material for each environment separately. Mainly, the parameters for which the values need to be identified are - temperature, partial pressures of CO^2 and H_2S, pH of brine or water produced, Cl content in this water phase and elemental sulfur presence. Additionally, corrosion damage during the acidizing process, damage that wireline tools cause during the wireline testing, corrosion and cracks sourced by completion fluids, well's oxygen contamination are also other parameters that provide information to select the correct wellbore materials (Brownlee, 2005).

Firstly, Craig introduced the data plots that are designed to select suitable alloys for HPHT and ultra-HPHT wells with the H_2S partial pressure up to 10,000 psi and temperatures up to 300°C (Craig, 1998). Piccolo et al. tested some materials such as steels (P-110 and C-110), supermartensitic stainless steel (S13Cr), duplex stainless steel, duplex stainless-steel wireline, superaustenitic stainless steel (N08535) and galvanized carbon stainless steel in HPHT gas condensate wells that produce high density brines. As a result of study, the best materials for different brine solutions in high corrosion rates were identified (Piccolo, 2005). Cao et al. investigated localized corrosions of corrosion resisted alloys for wells that contained hydrogen sulfur. The study combined model predictions with measurements for repassivation potential (E_{rp}), which allowed the identification of localized corrosion in different temperatures (ranges between 85°C to 232°C) and susceptibility of different corrosion resistant alloys to localized corrosion (Cao, 2016).

Cementing operations in HPHT wells are also challenging due to the effect of high pressure and temperature on the chemical and physical behavior of cements. Following cement placement operations, the challenge continues along the whole life of the well in setting the cement sheath. Generally, following the first two weeks of the cement operation, cement strength starts to decrease slowly, and it's called "cement retrogression". Prevention is possible by using 30% to 40% silica (Shadravan, 2012). Latest technological developments enabled the usage of nano technological materials in the oil and gas industry. Nano-Clays can be considered as the alternate option to set cement without cement retrogression (Mobeen, 2013).

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