INTERNATIONAL JOURNAL OF
INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Emerging Innovations in the Oil Industry: An Analysis of the Development of the Monodiameter Technology

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Abstract:
This paper discusses the development of the MonoDiameter Technology which is a form of technological innovation within the upstream sector of the petroleum industry. The upstream sector of the petroleum industry is concerned with geological prospects, drilling or oil extraction and production. In trying to improve our understanding of how technological innovation might occur in this sector of the industry, the model of organisational knowledge creation by Nonaka and Takeuchi is used in explaining the innovation processes. Based on this model, the article found out that technological innovation occurs by the interaction of both tacit and explicit knowledge under certain conditions (e.g. requisite variety, redundancy, creative chaos, autonomy and organisational intent). The paper also confirmed the existing literature on the role of collaborative arrangements as well as the presence of different drivers of technological innovation within the upstream sector (e.g. fluctuation of oil prices, fall in declared reserves, and rising cost of drilling due to exploitation of off-shore reserves).

Keywords: *Innovation, upstream petroleum industry, collaboration, tacit and explicit knowledge*

1. Industry Background

The petroleum industry has been valuable to the existence of humanity since the nineteen century and its importance has steadily increased overtime. The production and utilisation of this resource has generated immensely economic, social and environmental impacts, some of which according to Harris and Khare (2002) have not always been positive. Petroleum, otherwise referred to as crude oil and gas, is largely found within sedimentary rocks (sandstones, limestones, and rarely, claystones), although, it might occasionally be found in either igneous or metamorphic rocks (Selley, 2000). This according to Selley (2000: 24) is generally "genetically correlated to organic-rich source rocks of sedimentary origin that overlie the basement or have been intruded by igneous magma". A map showing the sedimentary deposits of the crude oil and gas is indicated in figure 1.

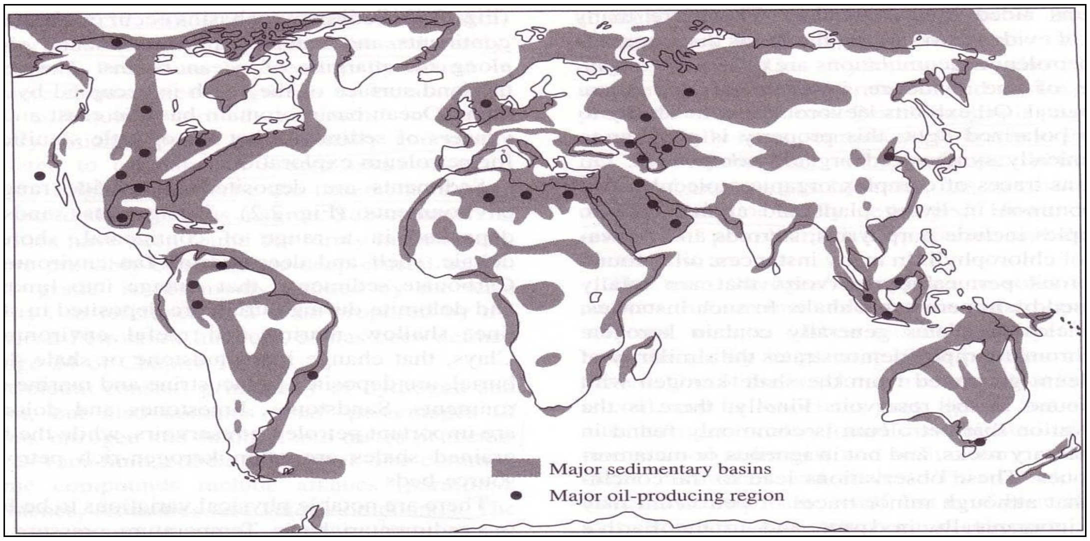

Figure 1: map showing sedimentary deposits
Source: adapted from Selley (2000: 26)

The industry, largely appear to have two distinct sectors: the downstream- petroleum refining, synthesis of organochemicals, transport and distribution and upstream- concerned with geological prospects, drilling or oil extraction and production (see Crabtree, et al. 1997)), although, a mid-stream sector (largely, transportation and distribution) is often separated from the downstream sector to form a separate category (see Harris and Khare, 2002). The classification by Crabree, et al. (1997) will however been used in this paper.

The fact that crude oil and gas are non-renewable resources means there is the possibility its depletion. Energy analysts once reported that world was going to run out of this resource in 1940 (World Oil, Feb. 2003). However, evidence from the petroleum industry shows today's depleted oil fields are frequently being replaced with lower quality fields, in terms of size and sometimes more complex reservoirs. Larger new finds are often found in the deepwater[1] (some examples include: the deepwater of Gulf of Mexico, Offshore Brazil, Gulf of Guinea, and the North Sea), which appears to introduce a variety of technological challenges, adding to the difficulties presented to maintain the current reserve levels. Technological innovation or development would seem therefore very crucial for the existence of this industry (Shelton and Percival, 2013; Kilisek, 2014).

Technological innovation has been considered to be important for the survival of firms in different sectors of the economy. Within the petroleum industry, its role has been vital for past, present and future petroleum developments (Power and Jewkes, 1992; Kilisek, 2014). Some examples of this include: the development of seismic techniques by geologists and geophysicists to generate large sum of data which are fed into supercomputers via the satellites to produce complex three-dimensional structural models of the earth (Bohi, 1999); the development of floating production platforms for water too deep for fixed-leg platforms (Ford, 2000); the development of the first Polycrystalline diamond cutters by General Electric in the mid-1970s; injection of carbon dioxide into Wells (Bhardwaj, 2014).

Technological innovation within the petroleum industry appears to be different in both sectors. Early innovative activities were predominantly within the downstream sector (Bower and Keogh, 1996). This, according to them was due to the fact that oil was easily produced from seemingly inexhaustible land-based reservoirs in the United States of America and the Middle East. This trend however, changed in the 1970s as oil companies were forced to search for crude oil and gas in more difficult environments, such as offshore exploration. A distinction of the innovation processes of both sectors (downstream and upstream) shows that, the technology generated in the downstream sector by the oil industry is usually kept 'proprietary', especially product innovations (Furtado, 1997: 1251). This, as expressed by Furtado (1997: 1247), "is because of its importance to market segmentation strategy… oil companies internalise most R&D efforts in that domain and have a low propensity to cooperate with other companies". This is in accordance with what is claimed by Nelson (1988), which is that collaboration or cooperation amongst companies seems easier when the kind of research carried out is barely kept proprietary or is specific. The upstream sector of the petroleum however, shows a more interactive innovation process between the oil companies and their oil service counterparts. This according to Furtado (1997) might be because the degree of appropriability is considered weak in this sector of the industry.

Technological innovation within the downstream sector of the petroleum industry as confirmed by Bower and Keogh (1996) has been extensively researched into by several academics (see also Enos, 1962); however, far too little attention appeared to have been paid to the technological innovation processes within the upstream sector of the petroleum industry. It is therefore the aim of this paper to improve on this by providing insights into the technological innovation processes within the upstream sector of the petroleum industry by analysing the development of the MonoDiameter Technology (a new way of well construction) through the use of the model of organisational knowledge creation by Nonaka and Takeuchi (1995).

2. The SECI[2] Knowledge Creation Process Nonaka and Takeuchi Model

This model provides the theoretical framework for understanding the development of the MonoDiameter Technology. This appears to be the best developed theory in the literature which can be used to explain knowledge – intensive innovation. According to Nonaka and Takeuchi (1995), without individuals being involved, an organisation cannot create knowledge. Therefore the concept of organisational knowledge creation should be understood as a process that "organisationally amplifies the knowledge created by individuals and crystallises it as a part of the knowledge network of the organisation" (Nonaka and Takeuchi, 1995: 239). Organisations cannot create knowledge without the involvement of individuals. Knowledge in other words is an abstract, essential and intrinsically individually centred phenomenon (Anderson, et al. 2000). Examples of the knowledge that employees in an organisation could have include: their competencies, skills, talents, thoughts, ideas, intuition, commitments, motivations, and imaginations (Prichard, et al. 2000).

This model involves new knowledge which stems from individuals being transformed into organisational knowledge. The model appears to have two parts:

- The interaction of tacit and explicit knowledge (socialisation – tacit to tacit; externalisation - tacit to explicit; combination- explicit to explicit; and internalisation - explicit to tacit (see figure 2). while tacit knowledge according to Nonaka and Takeuchi (1995: 60), "… is embodied within a person, and requires direct personal contact and experience to share…", explicit knowledge is knowledge that is transmittable in formal, systematic language. This form of knowledge is usually found in scientific journals and other academic literature (Nonaka and Takeuchi, 1995).

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[1] Generally refers to water depths greater than 300 metres.

[2] SECI- Socialisation, Externalisation, Combination and Internalisation

Socialisation (from tacit knowledge to tacit knowledge)	Externalisation (from tacit knowledge to explicit knowledge)
Internalisation (from explicit knowledge to tacit knowledge)	Combination (from explicit knowledge to explicit knowledge)

Figure 2: Four basic patterns for creating knowledge
Source: Adapted from Nonaka and Takeuchi (1995); modified by the author

In the socialisation mode (from tacit to tacit), it is a "process of sharing experiences and thereby creating tacit knowledge such as shared mental models and technical skills" (Nonaka and Takeuchi, 1995: 62). As such, a person can acquire tacit knowledge directly from others without using language – an example is, an apprentice working with his superior and learning the craftsmanship not only through language but through observation, imitation, and practice (Nonaka and Takeuchi, 1995: 63) (see also Mascitelli (2000)). The second mode is the externalisation (from tacit to explicit). This is a "process of articulating tacit knowledge into explicit concepts. It is a classic knowledge creation process in that tacit knowledge becomes explicit, taking the shapes of metaphors, analogies, concepts, hypotheses, or models" (Nonaka and Takeuchi, 1992: 64). According to Nonaka and Takeuchi (1995), "though it appears to be very difficult to express tacit knowledge into explicit knowledge and as such discrepancies exist, such discrepancies and gaps between images and expressions help promote reflection and interaction between individuals. Once explicit concepts are created, they can then be modelled" (Nonaka and Takeuchi, 1995: 64). Transforming knowledge from tacit to explicit appears to be very crucial for any organisation. The combination (from explicit to explicit) is the third mode. Combination is a "process of systemising concepts into a knowledge system" (Nonaka and Takeuchi, 1995: 67). This involves combining various bodies of explicit knowledge. People interact and combine the knowledge via media, documents, telephone conversations, meetings, or computerised networks (Nonaka and Takeuchi, 1995).

The final mode is the internalisation (from explicit to tacit). Internalisation is a "process of embodying explicit knowledge into tacit knowledge" (Nonaka and Takeuchi, 1995: 69). For this to occur, it helps if the knowledge is verbalised or written into various formats such as documents, manuals, or even oral stories. Such helps individuals within the organisation to internalise what they experienced, thus enriching their tacit knowledge (Nonaka and Takeuchi, 1995).

- Enabling environments created for this to occur.

These include – Intention (aspirations of the organisation), Autonomy (freedom of individuals to be creative within an organisation), Fluctuation / Creative Chaos (signals from within or outside the organisation that can help in creating new knowledge within the organisation), Redundancy (existence of information that goes beyond the immediate operational requirements of organisational members) and Requisite Variety (an organisation's internal diversity)

It is important to note that for technological innovation to within an organisation according to the model, there appear to be the successful interaction between tacit and explicit knowledge within these enabling environments. Having examined the literature, the criticisms of the Nonaka and Takeuchi model can be grouped under one area, which is the apparent distinction of knowledge into tacit and explicit knowledge.

In the area of the distinction between knowledge into tacit and explicit, Polanyi believes such a dichotomy is only artificial. According to Polanyi (1969), "While tacit knowledge can be possessed by itself, explicit knowledge is either tacit or has its root in tacit knowledge" (Polanyi, 1969: 114). What this means in essence is that tacit knowledge is the root of knowledge and explicit knowledge is an 'off shoot' of tacit knowledge. In other words it emanates from tacit knowledge. Other authors who critique Nonaka and Takeuchi on this include the following:

Tsoukas (1996) notes that "…although the preceding typologies [Nonaka and Takeuchi typology for example] have undoubtedly advanced our understanding of organisational knowledge by showing its multifaceted nature, they are also marked by certain limitations which stem, primarily, from the 'formistic' type of thinking that is inherent in any typology. Tacit knowledge is the necessary component of all knowledge; it is not made up of discrete beans which may be ground, lost or reconstituted… to split tacit from explicit knowledge is to miss the point - the two are inseparable" (Tsoukas, 1996: 14).

Stenmark (2002) stated that "… all knowledge is tacit…" (Stenmark, 2002: 5). "… Knowledge is based on personal experiences and cultural inheritance and fundamentally tacit…" (Stenmark, 2002: 9).

In Styhre's (2004) words, "… that the separation between tacit and explicit knowledge is a false problem because it simply does not rest on an elaborated ontological and epistemological discussion that satisfactorily clarifies the assumptions underlying such a division. We can not tell for sure where explicit knowledge ends and where tacit knowledge begins, because that is based upon the individual's ability to express and formulate him or herself. Tacit and explicit knowledge are not discrete categories, but always coexist in one another; all explicit knowledge presupposes some tacit skills, and tacit knowledge is always based on the use of explicit knowledge" (Styhre, 2004: 183).

While we tend to agree with the views that dichotomising knowledge as tacit and explicit could be inappropriate, this paper is less interested in such debate (as the scope of what knowledge is or what constitutes knowledge is beyond the scope of this paper) but is primarily focused on how to make use of the intellectual, intangible knowledge resources of organisations to create innovation. The model by Nonaka and Takeuchi helps in explaining how certain forms of knowledge- however it is- "tacit and explicit" knowledge interacts to develop the innovation of products. In other words, this means that though such dichotomy may be problematic, whatever expressions are used should be able to assist an organisation to create innovations.

3. Categories of Companies Upstream Innovation

The innovation process of the upstream industry shows three main groups as observed by Bower, et al. (1997):

- The Operators are referred to as oil users or oil companies (Furtado, 1997).

Stonham (2000) categorised this group of companies as the "Megamajors" (Stonham, 2000: 414), who are the industry shakers, for example; Royal Dutch Shell, BP, ExxonMobil, ENI Group, Total, Chevron. The "mezzos" (Stonham, 2000: 414) are smaller, mid-size companies, for example ConocoPhillips and independents which have broad product scope and geographic coverage, but are not world-class scale as are the first category. It is also claimed that these companies spend a substantial amount on research and development; for example, in 2002, according to Wetuski (2003), "ExxonMobil, BP and Royal Dutch/Shell spent a total of $450 million on research and development" (Wetuski, 2003: 24).

- The Prime Contractors are referred to as specialists by Stonham (2000) and oil suppliers firms by Furtado (1997).

These are large companies such as Schlumberger, Baker Hughes Inc, Halliburton Group, Wood Group, and Weatherford, which "undertake to supply a wide range of the services required (drilling and production services, construction, maintenance, logistics, and general oil-field support - focused either on specific products or parts of the value chain" (Bower, et al. 1997: 347; Keogh, et al.1998; Ernst and Steinhubl 1999). All these could be achieved through in-house capability, partnerships with both operators and contractors, and further direct subcontracting (Bower, et al. 1997: 347). The importance of the prime contractors in the generation of technological innovation can be observed according to Wetuski (2003); Neal (2007): Prime contractors such as "Baker Hughes, Halliburton, Weatherford, Schlumberger spent a total of $1.135 billion on research and development in 2002 and these prime contractors now account for 35% of the research and development that occurs in the upstream sector" (Wetuski, 2003: 24). This sudden change in the greater amount of money being spent on research and development by the prime contractors as against the oil operators could be attributed to high demand by the latter on technologies, which will save on costs and raise productivity, hence the huge amount being spent by the former.

- Smaller firms (for example, the Small Technology-Based Oil Related Companies- STBORs) offering a range of products and services mainly to the prime contractors.

This group, otherwise known as suppliers by Crabtree, et al. (1997), "fall into two categories: those which supply basic items such as nuts, bolts, and delivery services, and those which supply highly specialised products and services (STBORs). The latter category must invest in high levels of innovation to meet the needs of the fast changing, high-technology industry" (Crabtree, et al. 1997: 183) (see also Keogh, et al. 1998). Formerly, these groups had close and direct links with the Operators; however, this trend appears to have changed due to the greater reliance on complete out-sourcing by some of the main Operators to prime contractors (Crabtree, et al. 1997; Keogh, et al. 1998; Krahn, 1993; Bower and Young, 1995). Most Smaller Firms, therefore, rely on forming relationships with Prime Contractors (Bower, et al. 1997: 347).

Because of the changes in the upstream technology development, it is believed that the "future of this industry lies with the Operators and prime contractors" (Stonham, 2000: 414); Neal (2007). Furtado (1997) believes that the prime contractors are the main partners to Oil companies and that "upstream technology development and industrialisation is rather the outcome of the interaction between users (oil companies) and producers (oil supplies firms)" (Furtado, 1997: 1252).

4. Conventional Well Construction Method

To understand what this technology- Solid Expandable Tubular and its ultimate application, the MonoDiameter Technology- means to the well construction industry, it is necessary to first explain what conventional well construction is. Wells are constructed for three main purposes according to Jenner (2003):

- Exploration - that is to drill into formation where hydrocarbons are suspected;
- Appraisal - to drill into the reservoir to confirm commerciality of hydrocarbon reserves and to delineate the aerial reservoir extent; and
- Development - wells for the production of reservoir fluids or the injection of water or gas to lift products to the surface.

As a well is drilled, the drill bit passes through a number of formations before a potential reservoir is reached. According to Skinner (1981), it is important that some of these formations are sheltered as they may interfere with later drilling activities. To drill a well, therefore, requires a hole of a certain diameter to be drilled. When the well is drilled, it is lined with a casing string[3] and to set this in place, cement mixed with water in a thin liquid is pumped down the casing and allowed to circulate up to the surface in the area between the casing and the wellbore. With the hardening of the cement, both the cement and the casing form a complete seal against any possible contamination of the aquifer[4] (Skinner, 1981).

Once this is done, it is expected that you will have to drill down the casing. This obviously means that the next part of the hole that is drilled is of a smaller diameter than the first. Hence, you will require a change in the drill bits; a smaller one to enable it to pass through the first section of casing. Once the next length of well has been drilled, this is again lined with casing pipe and cemented in place, with the annular space between the casing string and the borehole being filled with cement. This continues, with the diameter of the well reducing as it gets deeper until oil or gas reservoir is reached (Shell Technology E&P). Most decisions regarding casing

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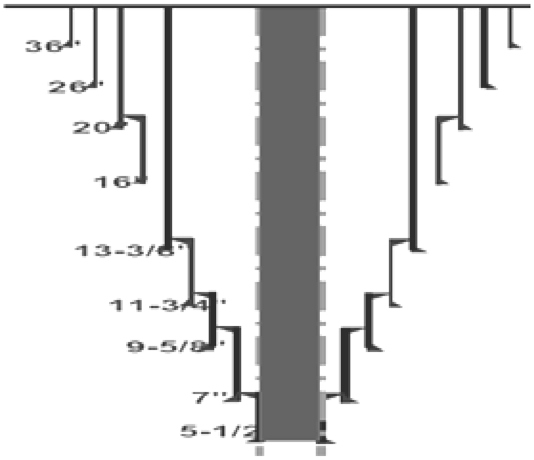
[3] Casing strings are the steel used in well construction.

[4] "A great deal of the world's drinking water supply comes from shallow, fresh-water aquifers. These aquifers", according to Skinner (1981: 45), often occur within a few hundred feet of the earth's surface and obviously it would not be desirable to allow mud filtrate to enter these aquifers if they supply water used for human consumption or irrigation.

strings, casing sizes, setting depths, and cementing methods are governed by different regulations (Skinner, 1981). An example of this is in the North Sea, where a 30 inch casing string is generally set at approximately 100 feet into the ground to which help in supporting unconsolidated formations at the surface (Ford, 2000). (see figure 3 for illustration of the conventional well construction).



Total depth (TD)[5] - 25, 000 ft.

Figure 3: Conventional well constructions
Source: Adapted from Dewar (2002)

From figure 3, the first casing string was of 36-in, the next 26-in and then 20-in and when the total depth is reached, the casing sting required was 5 1/2 –in. The telescopic nature of the conventional casing method has therefore been a fundamental problem for the petroleum industry (World Oil, Feb. 2003), because it results in wells not being fully explored in terms of its petroleum deposits. Conventional casing programs have especially presented “challenges for operators of deepwater and deep or extended-reach wells” (Oil and Gas Investor, May 2002: 2). This is because, when a well is drilled, it is not just the depth that causes a lot of problem, but also the various geological formations which may be encountered during drilling. Such geological formations might include unstable clay and shale formations, salt deposits, shallow water flows, pore pressure/fracture gradient issues. At the well’s penetration of each of these formations, an additional string of casing may have to be set to permit drilling to continue safely and this can reduce the internal diameter of the well earlier than desired and lead to a situation where the well could run out of sufficient hole size and the reservoir cannot be reached” (Shell Technology E&P). In some cases, “10 or more strings of casing might be required causing the telescopic effect to become the main driver for well costs” (World Oil, Feb 2003: 15). The introduction of the MonoDiameter Technology is therefore directed towards addressing the telescopic nature of conventional well construction.

5. The MonoDiameter Technology

Expandable tubular technology involves two types- the slotted tubular technology usually used in completions and production and the solid expandable tubular technology used in well construction. This paper is interested in the solid expandable tubular technology (its application leads to the MonoDiameter Technology). Solid expandable tubular technology attempts to address the short-coming of the conventional casing design. Solid expandable tubular technology or solid tube expansion technology offers “the drilling industry the opportunity to access smaller deepwater reservoirs that were previously uneconomical due to the traditional high costs of deepwater technology and operations” (Petroleum Economist, March, 2003: 15). It also offers “significant cost savings in conventional well construction and well remediation environments” (Petroleum Economist, March, 2003: 15. 15). In well construction, the “solid expandable tubular can be used to minimise the well tapering, thus optimising the well’s design. This allows the operator to construct wells with smaller tubulars in the upper portions of the wellbore while still penetrating the reservoir with production that is optimum for maximum hydrocarbon recovery” (World Oil, February, 2003: 16). While the first generation of the solid expandable tubular allows for the reduction in the well tapering, the ultimate objective of the MonoDiameter Technology is to eliminate the telescopic effect in well engineering and constructions (see World Oil, February, 2003).

The expandable tubular technology concept was a direct response by the “oil industry to the effects of the tapering of the wellbore and the industry confronted this dilemma with innovative problem solving that stretched the boundaries of physics” (Cales, 2003: 1). It is believed that the development of the technology started in the 1980s when Royal Dutch Shell started to investigate the radical concept of using expandable tubulars to overcome the telescopic nature of well designs, a problem in drilling since the mid-nineteenth century (World Oil, Feb 2003: 16; Adkins 2002). Shell engineers envisioned a technology that would ultimately result in a single-diameter wellbore that would bring “well cost savings in the order of 30% to 50% long-term” (World Oil, Feb 2003: 16).

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[5] It is important to note that in reality, Well construction might not be in this simplified form

The MonoDiameter well construction process involves installing a MonoDiameter drilling liner below the casing and expanding it and the overlap. The resulting "internal diameter will allow additional MonoDiameter drilling liners to be installed and expanded without reducing the internal diameter as experienced in a standard telescoping casing program. Thus, the expansion creates a single internal diameter" (Hart's E&P, 2003; 13). It is, therefore, created when the "overlaps of the nested expanded casing liners are 'over-expanded', resulting in a single-diameter wellbore. These type of well exhibits the ultimate diametric efficiencies - a constant inside diameter from top of the well to its total depth" (Dupal, et al. 2002: 44). For example, a "MonoDiameter system would include 11-3/4 inch standard casing string followed by 9-5/8 inch MonoDiameter drilling liner- expanding the 9-5/8 inch MonoDiameter liner in the 11-3/4 base casing in the overlap creates an internal diameter of 10.4 inch. Additional 9-5/8 inch MonoDiameter liners can be expanded to continue the 10.4 inch internal diameter for as long as the casing design requirement" (Hart's E&P, 2003: 13) (see figure 4 for MonoDiameter Technology).

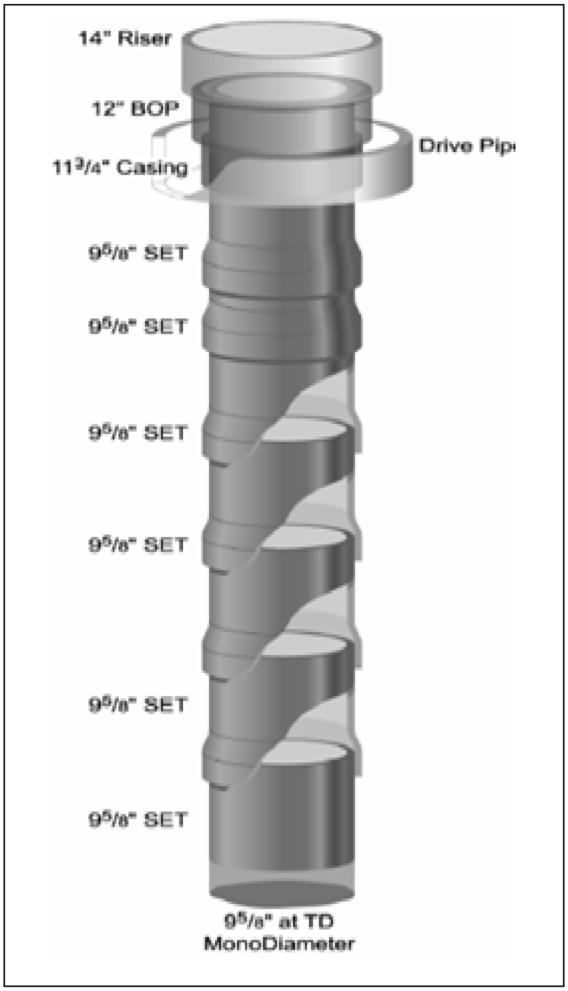

Figure 4: MonoDiameter Technology
Source: Adapted from Dewar (2002)

The development of the MonoDiameter Technology by Royal Dutch Shell involved the formation of some collaborative arrangements. At the initial phase, Royal Dutch Shell licensed an Aberdeen based company, Petroline to develop the slotted expandable tubular. At approximately the same time that Shell was involved in the development of expandable slotted tubular technology with Weatherford (having bought Petroline), they were looking for how to advance the other classified type of expandable tubular technology, which is solid expandable tubular. This led to Royal Dutch Shell forming two joint ventures with Baker Hughes to form E2Tech and Halliburton to form Enventure Global Technology (see figure 5). Whilst the joint venture arrangement between Royal Dutch Shell and Halliburton (Enventure Global Technology) still exist, that of the E2Tech got dissolved, with Royal Dutch Shell acquiring the interest of Baker Hughes and eventually licensing it to Weatherford.

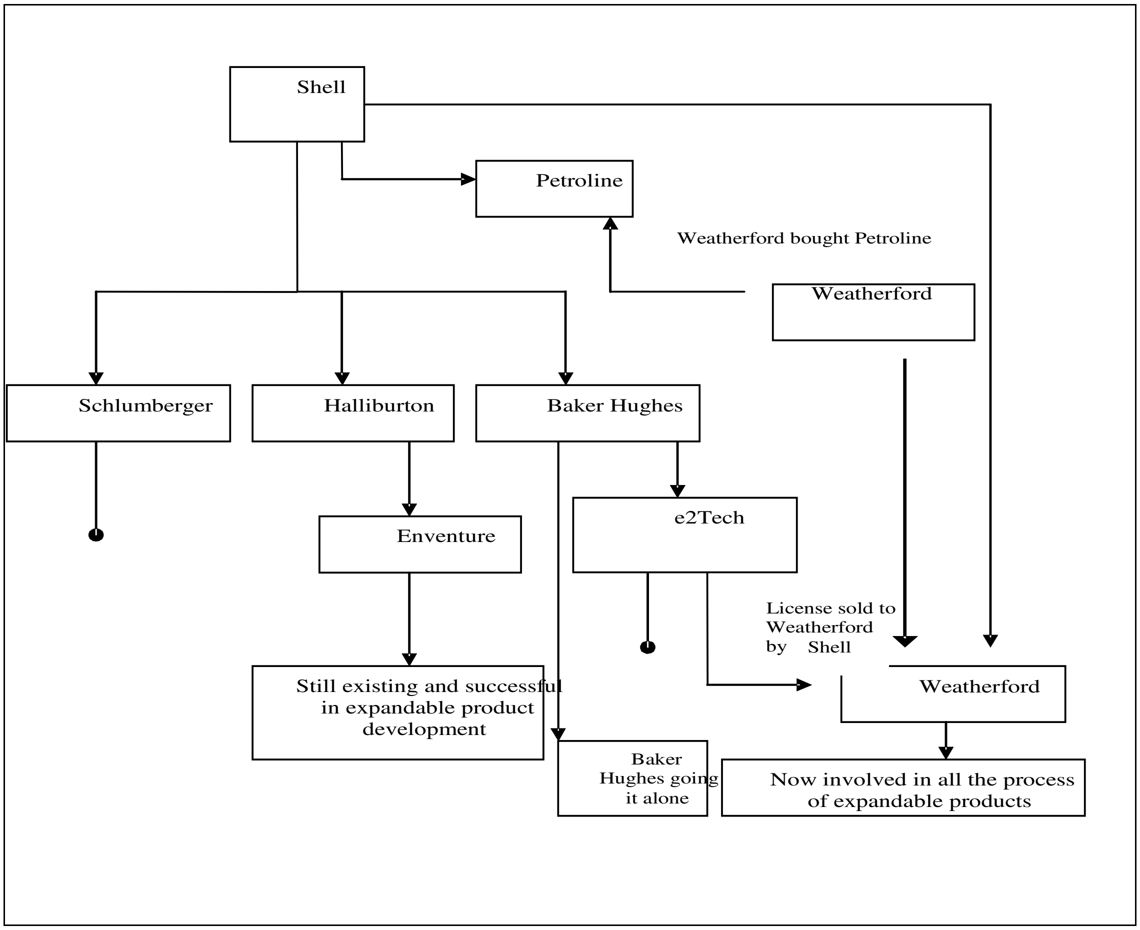

Figure 5: collaborative arrangements in the development of the MonoDiameter Technology
Source: Tebepah (2005)

Because the concept of expandable technologies was new to the petroleum industry in general, some key problems in particular could be observed, which were notably:

i. Steel to be expanded. The challenge was to learn how to expand the oilfield tubulars familiar to the petroleum industry;
ii. The issue of Connectors. When trying to run pipe into the well, there has to be some mechanism of linking the various pipes together that will survive, but not affect the expansion process;
iii. The issue of the tool string used for expanding the pipes in a single trip.
iv. The issue of the lubrication, which is to be used during the expansion process.

A summary of the innovation sequence is indicated in figure 6

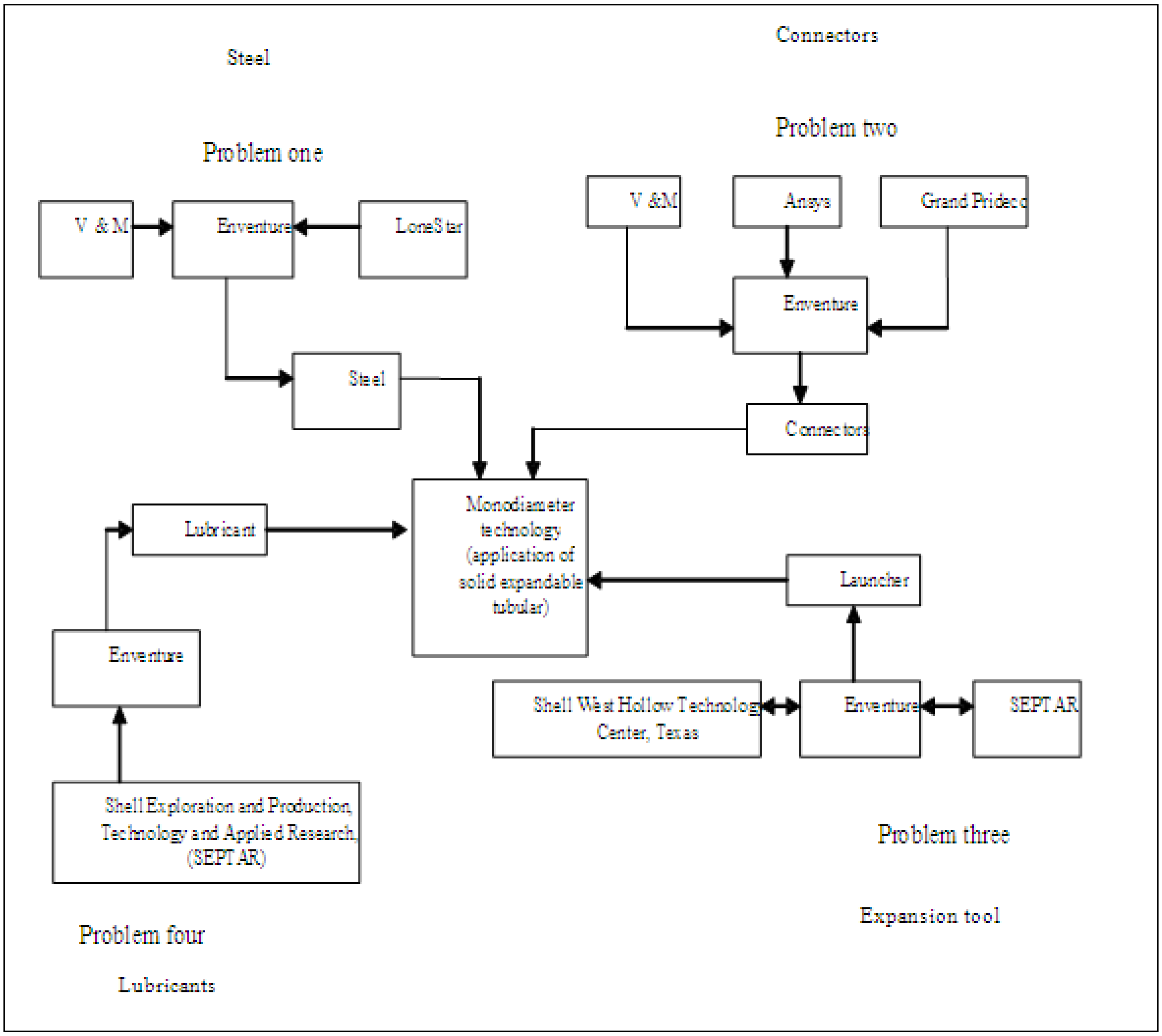

Figure 6: innovation sequence of the MonoDiameter Technology
Developed by the author

6. Findings from the Development of MonoDiameter Technology

The model by Nonaka and Takeuchi (1995) appear to provide a good explanation on the development of the MonoDiameter Technology. As indicated earlier in this paper, the Nonaka and Takeuchi model appear to have two parts- the interaction of tacit and explicit knowledge and the creation of enabling environments that encourages such interaction.

The development of the MonoDiameter Technology shows the socialisation mode (tacit to tacit) started through the insight an inventor within Royal Dutch Shell acquired from the bottle of whiskey at the airport and subsequent interaction with his colleague on the lining of a borehole. (This later expanded into a larger self organising team which, as claimed by one of the interviewees, had autonomy and was free to interact with the external environment (examples of such interactions were with joint venture partners, manufacturers of various parts of the technology- see figure 6). It was therefore likely that these kinds of processes allowed for the socialisation of knowledge. The next phase represents the creation of concepts otherwise referred to as externalisation (tacit to explicit) mode. The mental model acquired from the plastic nettings (which expands and contracts) over the bottle of whiskey the inventor, and shared with his colleague, was successfully linked to well construction and it would appear the following concepts were created:

- A steel that has the tendency of expanding downhole without rupturing (example, crumple zone of car);
- The idea of linking the pipes (steel) together which would not prevent the expansion of the pipes – the connectors;
- An expansion mechanism that could expand the steel and connectors without itself being brittle;
- A lubricant to allow for easier expansion of the steel.

Although we did not observe the process of communication directly, it does appear that there was an open access line of communication which helped in facilitating both the first and second phase interaction process established to enable anyone to call from anywhere in the world. This was the daily meeting which seems like a time for exchanging information, raising potential issues, solving problems and reviewing next steps. They also had conferences on the expandable tubular technology forum every 6 months and associated with this were various social events. All of these processes could have facilitated the socialisation and externalisation phases.

The concepts created appear to have been justified against the three key organisational intentions of the company (cost savings, increase in production and increase in reserves). Built on both newly created explicit knowledge on expandable tubular technology and existing explicit knowledge on well construction, various prototype products or archetypes were developed. This represents the combination mode (explicit to explicit). Some examples of such prototype products include the seamless L-80 casing, ceramic cone, and pipes being linked together by welding. These were rejected when certain drawbacks were found.

Evidence on the last phase, internalisation of the knowledge, will seem to be found by the suppliers of various parts of the technology. For example, the apparent success of the expandable steel (LSX 80) developed by LoneStar and Enventure (in terms of it expanding without rupturing), Royal Dutch Shell appear to have encouraged other steel manufacturers such as V&M, Sumitomo and Marubeni Itochu to be involved in development of expandable steel. Another example is the development of the expansion medium by Enventure Global Technology (the expansion cone), which appears to have encouraged other competitors to develop rival products.

The creation of enabling environment that facilitates the interaction of both tacit and explicit knowledge is the second part of the model presented by Nonaka and Takeuchi (1995). The enabling environment is necessary if the interaction of both tacit and explicit knowledge is to be successful. The following were observed:

6.1. Intention

The organisational intention, “which is defined as an organisation’s aspiration to its goals” (Nonaka and Takeuchi, 1995: 74), is one of the key conditions for organisational knowledge creation, which leads to innovation in an organisation. Based on the interviews conducted, three key organisation intentions were observed –technology that reduces cost of drilling, raised production levels and increase the reserves.

6.2. Autonomy

The second condition for promoting the knowledge spiral that ultimately leads to innovation according to the model is autonomy - “with original ideas emanating from autonomous individuals, diffusing within the team and then ultimately becoming organisational ideas” (Nonaka and Takeuchi, 1995: 76). This appears also to be present in the team responsible for the technology. According to one of the interviewees consulted, their bosses, the innovators were given the freedom to carry out the innovation.

6.3. Creative Chaos

The oil industry appeared to have been faced with real crisis during that period. Examples were the volatility of oil prices- which comprises of very high oil prices and very low prices (oil glut) in the periods of the 1970s and 1980s (see Dargay and Gately, 1995); dwindling oil reserves (Bentley, 2002, Campbell and Laherrere, 1998) and rising costs of operations- particularly in the offshore operations (evidence based on interviews). This appeared to have spurred the management of Shell into a search for possible solutions that will provide cost savings, increase its production and raise its reserves (these were all the organisational intention).

6.4. Redundancy

Redundancy is the fourth condition that enables the knowledge spiral to take place organisationally. Although, redundancy through the strategic rotation of personnel is common to Royal Dutch Shell according to one of the interviewees, we did not find any evidence of this occurring in the development of this technology.

6.5. Requisite Variety

The final condition that helps to advance the knowledge creation process according to the model is the requisite variety. Evidence of this appears to have existed in the development of the MonoDiameter Technology. Royal Dutch Shell seemed to have developed a flat organisational structure to deal with the development of the technology (see figure 7). The figure shows 2 creative staff, 7 scientists, 7 laboratory technicians, 4 global implementation team members and 7 regional engineers.

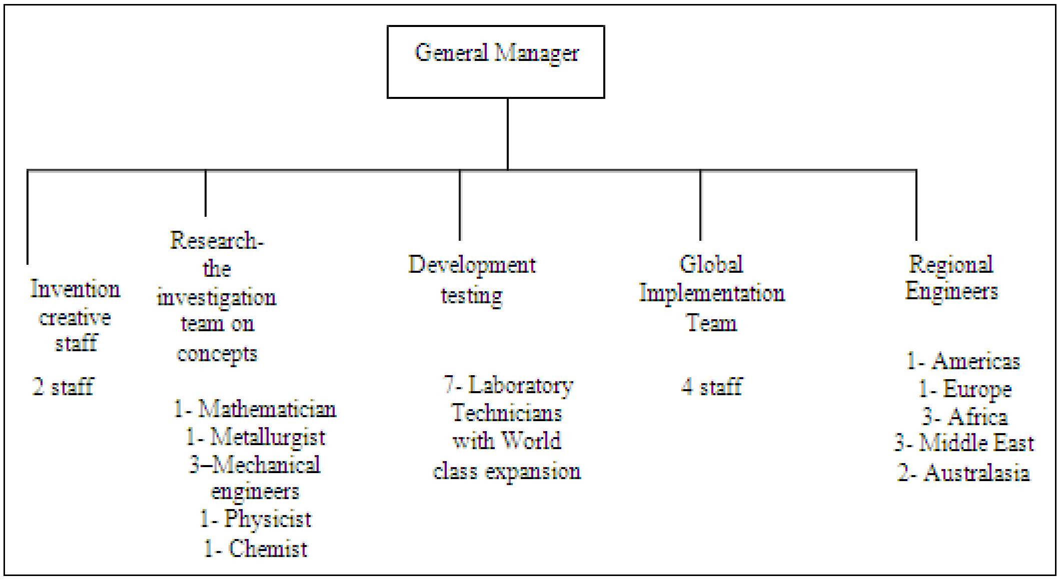

Figure 7: Expandable Technology Team
Source: Dewar (2004), modified by author

The development of the MonoDiameter Technology also confirms the role in which technological collaboration plays in technological innovation, particularly when such knowledge is not found within the organisation. Technological innovation appears to have moved from the stage where a "heroic individuals" pioneered ideas into action to a situation where innovation is increasingly the product of networked activity (Tidd, et al. 2001: 28; Rothwell, 1992 - see the fifth general innovation model). The increase in the complexities of products and services means that no single firm, however well endowed, can innovate on its own and therefore it makes sense to collaborate and build on complementary strengths. According to Leonard-Barton (1996: 136), the "ability of a firm to recognise the value of new, external information, assimilate it, and apply it to commercial ends is critical to its innovative capabilities". Hence, the importance of importing knowledge from external technology sources in the knowledge creating process is deemed highly important (Leonard-Barton, 1996). Importing external knowledge is usually done when the company concerned believes that there is a "capability gap" that exists in its innovative capabilities (Leonard-Barton, 1996: 138).

The model by Nonaka and Takeuchi tends to agree with the importance of collaboration in the development of technological innovation, particularly in the socialisation phase. The tacit knowledge from collaborating organisations is seen as an important source, particularly when there is the absence of such within the organisation.

Since the MonoDiameter technology is concerned with well construction which according to an interviewee within Royal Dutch Shell is not the core business of the company, it had to involve companies that had such capabilities. As a result, Royal Dutch Shell collaborated with two oil service companies - Halliburton and Baker Hughes - to form Enventure Global Technology and E2Tech, respectively. Both collaborations were joint venture agreements, although, E2Tech was eventually dissolved and the license sold to Weatherford. The importance of collaboration can also be observed in the development of parts of the technology. Examples include: the development of the steel with Lone Star and V&M; and the development of connectors as a result of the collaboration with Grand Prideco, V&M, and Ansys (see figure 6)

Following the evaluation of the development of the MonoDiameter Technology, several factors seem to drive the process of the innovation of the technology. We classify these broadly in terms of market conditions and technical problems. While technical problems appear to be factors that are within the control of companies (for example, well tapering), market conditions (these are similar to the enabling environment of fluctuation and creative chaos based on the model by Nonaka and Takeuchi) are outside the control of the companies (for example, volatilities in oil prices, rising cost of drilling). The technical problems become more significant when the market conditions become more severe. In other words, these market conditions increase the incentives for companies to try and solve these technical problems (see figure 8). The technical problems are considered as the routine difficulties associated with the operations of the companies on the field, for example, well tapering. These companies, however, appear to have been coping with the various shortcomings of these technical problems. Deteriorating market conditions, however, force the company's R&D effort towards innovation. These market conditions propel the companies to act as the effect of not responding might lead to huge losses in market shares or reduction in profitability.

The implication of this is that successful innovation is likely to occur when a need and the means of resolving it co-evolves. How much is spent on the Research and Development Department by the company is therefore crucial because it gives the company the capability to solve problems

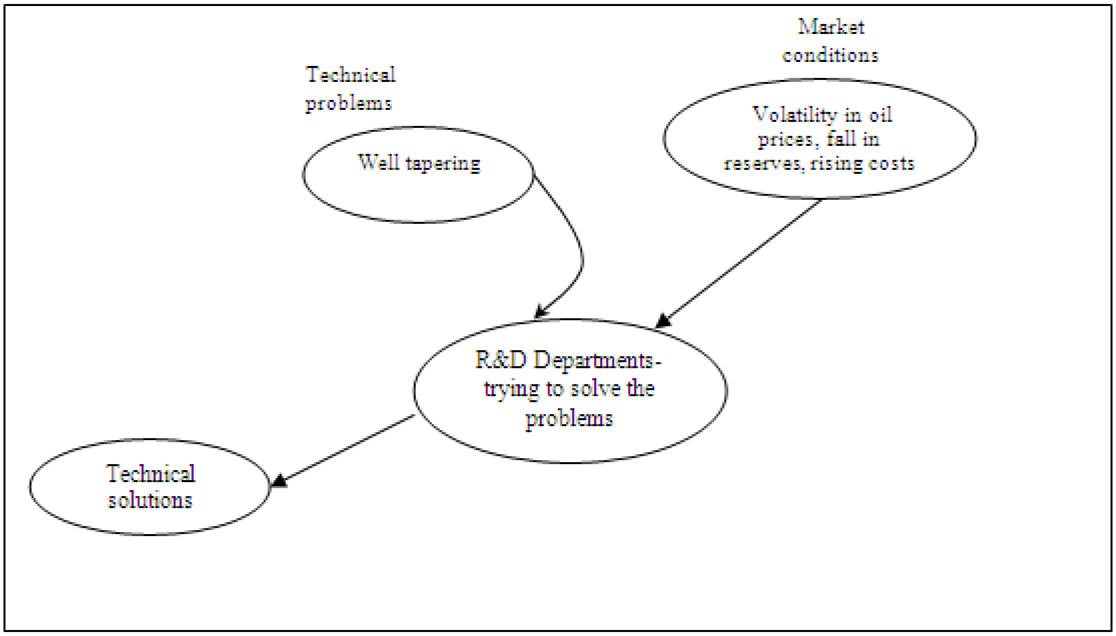

Figure 8: Innovation drivers of the MonoDiameter Technology
Source: Tebepah (2005)

7. Conclusions

This article attempts to shed light on emerging innovations within the upstream sector of the petroleum industry. This is aimed to develop a better understanding, principally through the development of the MonoDiameter Technology by the Royal Dutch Shell and its collaborating partners (these were based on interviews and other secondary data sources). The framework of the SECI model of knowledge creation by Nonaka and Takeuchi was used in explaining how the innovation occurred.

Based on the model by Nonaka and Takeuchi, the paper found out that technological innovation occurs by the interaction of both tacit and explicit knowledge under certain conditions (e.g. requisite variety, redundancy, creative chaos, autonomy and organisational intent). This paper therefore believes an organisation having either tacit or explicit knowledge alone will find it difficult to create innovation. Innovation will appear to be possible under certain conditions which allows for the interaction of both forms of knowledge. The article also confirmed the existing literature on the rising importance of collaborative arrangements as well as the existence of different drivers of technological innovation within the upstream sector (e.g. fluctuation of oil prices, fall in declared reserves, and rising cost of drilling due to exploitation of off-shore reserves).

8. References

i. Adkins, M. (2002) Shell and Halliburton push new oil field technology, Alexander's Gas & Oil Connections.
ii. Bentley, R.W. (2002) Global Oil and Gas Depletion: An Overview, Energy Policy, 30, 189-205.
iii. Bhardwaj, A. (2014), Best Technological innovation being used by top 20 Oil and Gas and Utility Companies. Web document, https://www.linkedin.com/pulse/20140826183211-22741080-best-technological-innovation-being-used-by-top-20-oil-gas-utility-companies accessed on the 9th June, 2015
iv. Bohi, D. R. (1999) Technological Improvement in Petroleum Exploration and Development in Productivity in Natural Resource Industries. In Simpson D.R (Ed). Improvement through Innovation. Washington, Resources for the Future.
v. Bower, D. J., Crabtree, E., and Keogh, W. (1997) Rhetorics and realities in new product development in the subsea oil industry, International Journal of Project Management 15(6): 345-350.
vi. Bower, D. J. and Keogh, W. (1996) Changing patterns of innovation in a process dominated industry, International Journal of Technology Management 12(2): 209-220.
vii. Bower, D. J and Young, A. (1995) Influences on Technology Strategy in the UK Oil- and Gas-related Industry Network, Technology Analysis and Strategic Management 7(4): 407-416
viii. Cales, G. L. (2003) The Development and Applications of Solid Expandable Tubular Technology, Petroleum Society's Canadian International Petroleum Conference, Calgary, Alberta, Canada, Petroleum Society Journals.
ix. Campbell, C.J., and Laherrere, J.H. (1998) The End of Cheap Oil, The Scientific American, Vol. 278, Iss.3, Pg. 60
x. Crabtree, E., Bower, D.J and Keogh, W. (1997) Conflict or Collaboration: The Changing Nature of Inter-firm Relationship in the UK Oil and Gas Industry, Technolgy Analysis and Strategic Management 9(2): 179-191.
xi. Dargay, J., and Gately, D. (1995) The Response of World Energy and Oil Demand to Income Growth and Changes in Oil Prices. In Socolow, Anderson and Harte (Eds.) in Energy and the Environment, , Annual Reviews Inc., Palo Alto, CA, USA

xii. Dupal, K. K., Campo, D.B., Andrews, C.J., Cook, R.L., Ring, L.M., and York, P.L (2002). Realisation of the Mono-Diameter Well: Evolution of a GameChanging Technology, Offshore Technology Conference, Houston, Texas, Enventure Global Technology.

xiii. Enos, J.L (1962), Invention and Innovation in the Petroleum Refining Industry. In R.R. Nelson (Ed), The rate and Inventive Activity: Economic and Social Factors. Princeton, N.J, Princeton University Press, pp 299-321

xiv. Ernst, D and Steinhubl, M.J (1999) Petroleum: after the mega-mergers, McKinsey Quarterly

xv. Ford, J. (2000) Drilling Operations. In R.A. Dawe (Ed), in Modern Petroleum Technology Volume 1 Upstream, West Sussex, England, John Wiley and Sons Limited.

xvi. Furtado, A. T. (1997) The French system of innovation in the oil industry - some lessons about the role of public policies and sectoral patterns of technological change in innovation networking, Research Policy 25: 1243-1259.

xvii. Harris, R. and Khare, A. (2002) Sustainable development issues and strategies for Alberta's oil industry, Technovation, Volume 22, Number 9, September 2002, pp. 571-583(13)

xviii. Hart's E&P (2002) Solid Expandable Tubulars - reduce costs; assure geological objectives; accelerate production; precursor to Monodiameter, World Oil

xix. Jenner, J. W. (2003) Drilling and Well Construction. London, Institute of Petroleum Training Program.

xx. Keogh, W., Jack, S.L., Bower, D.J., and Crabtree, E (1998) Small, Technology-based Firms in the UK Oil and Gas Industry and Internationalisation Strategies, International Small Business Journal 17(1): 57-72.

xxi. Kilisek, R. (2014), Origins of the next wave of innovation in the oil and gas industry, Web document, http://theenergycollective.com/jared-anderson/422976/infographic-origins-next-wave-innovation-oil-gas-industry Accessed on the 15th June, 2015

xxii. Krahn, D. (1993) Vital Links, the service sector and the North Sea Oil Industry. Waterfront Partnership's Petroleum Revenue Tax Conference, London, Cafe Royal.

xxiii. Leonard-Barton, D. (1988) Implementation as mutual adaptation of technology and organisation, Research Policy 17: 251-267.

xxiv. Mascittelli, R. (2000) From Experience: Harnessing Tacit Knowledge to Achieve Breakthrough Innovation, Journal of Production Innovation Management 17: 179-193.

xxv. Neal, H (2007), Technology Development and Deployment, Working Document of the NPC Global Oil and Gas Study, Web Document. http://www.npc.org/study_topic_papers/26-ttg-ogtechdevelopment.pdf. Accessed on 14th May, 2009

xxvi. Nelson, R. (1988) Institutions supporting technical change in the United States, in Dosi, G., Freeman, C., Nelson, R., Silverberg, G., and Soete, L (eds)., Technical Change and Economic Theory. London and New York, Pinter.

xxvii. Nonaka, I and Takeuchi, H (1995) The Knowledge Creating Company. New York and Oxford, Oxford University Press.

xxviii. Polanyi, M. (1969) Knowing and being. London, Routledge.

xxix. Power, M and Jewkes, E (1992) Simulating the discovery rate implications of technological innovation in oil and gas exploration, Technological Forecasting and Social Change (41): 161-175.

xxx. Prichard, C., Hull, R., Chumer, M., and Willmott, H (Eds) (2000). Managing Knowledge-Critical Investigations of Work and Learning, Basingstoke, McMillan Business.

xxxi. Rothwell, R. (1992) "Successful industrial innovation: critical success factors for the 1990s." R&D Management 22(3): 221-239.

xxxii. Selley, R. C. (2000) Geoscience. In R.A. Dawe (Ed), in Modern Petroleum Technology Volume 1 Upstream, West Sussex, England, John Wiley and Sons Limited.

xxxiii. Shelton, R. and Percival, D. (2013), Gateway to Growth: Innovation in the Oil and Gas Industry, Web Document, http://www.pwc.com/en_GX/gx/oil-gas-energy/publications/pdfs/pwc-gateway-to-growth-innovation-in-the-oil-and-gas-industry.pdf accessed on the 15th June, 2015

xxxiv. Skinner, D. R. (1981). Introduction to Petroleum Production. Houston, Gulf Publishing Company

xxxv. Stenmark, D. (2002) The Relationship between Information and Knowledge and the Role of IT in Knowledge Management, 104b, 35th Annual Hawaii International Conference on System Sciences (HICSS'02)-Volume 4

xxxvi. Stonham, P. (2000) BP Amoco: Integrating Competitive and Financial Strategy. Part one: Strategic Planning in the Oil Industry, European Management Journal 18(4): 411-419.

xxxvii. Styhre, A. (2004) Rethinking Knowledge: A Bergsonian Critique of the Notion of Tacit Knowledge, British Journal of Management Volume 15 Issue 2 Pg. 177 - June

xxxviii. Tebepah, E (2005) Technological Innovation in the Upstream Sector of the Petroleum Industry, an Unpublished PhD Thesis, Manchester Business School, University of Manchester, United Kingdom.

xxxix. Tidd, J., Bessant, J., and Pavitt, K. (2001) Managing Innovation: integrating technological, market and organisational change. Chichester, West Sussex, England, John Wiley and Sons Ltd.

xl. Tsoukas, H. (1996) The firm as a distributed knowledge system: A constructionist approach, Strategic Management Journal. 17 (Winter Special Issue) 11-25

xli. Wetuski, J. (2003) Technology is great, but who is going to support the cost? Oil and Gas Investor 23, (7): 24.

xlii. World Oil. (2003) Today's technology and its applications: Expandable Tubular Technology is used in all facets of well life to reduce costs and increase production.World Oil 224(2 pS5(8)).